OPTIMAL DESIGN OF A SINGLE POINT TURNING TOOL AND COMPUTER GRAPHIC SIMULATION OF THE CHIP FORMATION PROCESS

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CERTIFICATE

CERTIFIED that the thesis titled, 'OPTIMAL DESIGN OF A SINGLE POINT TURNING TOOL AND COMPUTER GRAPHIC SIMULATION OF THE CHIP FORMATION PROCESS' has been submitted by Mahendra R. Jajoo under our supervision and that this work has not been submitted elsewhere for award of a degree.

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NOMENCLATURE

α	-	Back rake angle
α_o	-	Normal rake angle
β	-	Side rake angle
β_o	-	Normal relief angle
γ	-	End relief angle
∂	-	Side relief angle
θ	-	End cutting edge angle
$\emptyset$	-	Side cutting edge angle
$\emptyset_{max}$	-	Maximum permissible side cutting edge angle
$\emptyset_p$	-	Plan approach or entering cutting edge angle
λ	-	Inclination angle
λ'	-	Exponent of speed in equation of cutting forces
V_{max}	-	Maximum cutting speed permissible
V_{min}	-	Minimum cutting speed permissible
s_{max}	-	Maximum feed permissible
s_{min}	-	Minimum feed permissible
t_{max}	-	Maximum depth of cut permissible
t_{min}	-	Minimum depth of cut permissible
R_a	-	Surface roughness
BHN	-	Warkpiece hardness in BHN
C'	-	Cost of machining per piece
h_f	-	Width of wear land
n	-	Exponent of tool life equation
T	-	Tool life
b_{max}	-	Maximum width of cut permissible
u	-	energy per unit valume
E	-	Young's Modulus
K_α	-	Constant giving effect of rake angle on cutting forces
$K_\emptyset$	-	Constant giving effect of side cutting edge angle on cutting forces

K_v - Constant giving effect of cutting speed on cutting forces

K_r - Constant giving effect of nose radius on cutting forces

K_{h_f} - Constant giving effect of tool wear on cutting forces

K_{cf} - Constant giving effect of cutting fluid on cutting forces

K_m - Material constant

L_e - Tool overhang

P_R - Production rate

P_x, P_y, P_z - Compnents of cutting force

p - Exponent of feed in Granovsky's emperical law

q - Exponent of depth of cut in Granovsky's emperical law

r - Nose radius

s - Feed

t - Depth of cut

t_1 - Idle time per piece

t_c - Cutting time per piece

t_d - Tool changing time

T - Tool life

η - Efficiency of motor

x - Exponent of depth of cut in force equation

y - Exponent of feed in force equation

R - Initial chip curvature

C - Constant of tool life equation

Δ - Tool deflection permissible

σ - Permissible stress of tool shank material

L - Length of tool bit

B - Width of the tool

H - Height of the tool

α_{opt} - Optimum rake angle

σ_u - Ultimate strength of material

ABSTRACT

An interactive package is developed to design a single point turning tool for optimal results. The program gives option to the user to select the work and tool materials. The geometry of the tool and the results of the cutting process are displayed on the terminal. The program gives a graphic display of isometric view of the tool followed by display of chip formation process in its animated form. The package gives a multistage optimization of speed, feed and depth of cut, which gives the cutting conditions for the best performance of the designed tool in the specified set of constraints. A methodology is developed to optimize the tool geometry parameters by studying the effect of these parameters on the constant and exponents of the tool life equation.

CHAPTER 1

DESIGN OF A CUTTING TOOL

1.1 Introduction

The primary method of imparting form and dimension to a workpiece is the removal of material by the use of edged cutting tools. Almost all cutting tools used in metal cutting operations consist of the basic form of a wedge. Cutting tools are designed with sharp edges to minimize rubbing contact between the tool and workpiece. Variations in the shape of the cutting tool influence tool life, surface finish of the workpiece and the amount of force required to shear a chip from the parent metal. The various angles ground on a tool bit are called the basic tool angles and compose what often is termed as tool geometry.

The geometry of a turning tool essentially consists of the following elements: face or rake surface, flank, cutting edges and the corner. Face is the surface of the cutting tool along which the chips flow out. Flank surfaces are those facing the workpiece. There are two flank surfaces, principal and auxiliary flank surfaces. Principal cutting edge performs the major portion of cutting and is formed by intersecting line of the face with the principal flank surface. Auxiliary cutting edge is formed by the intersection of the

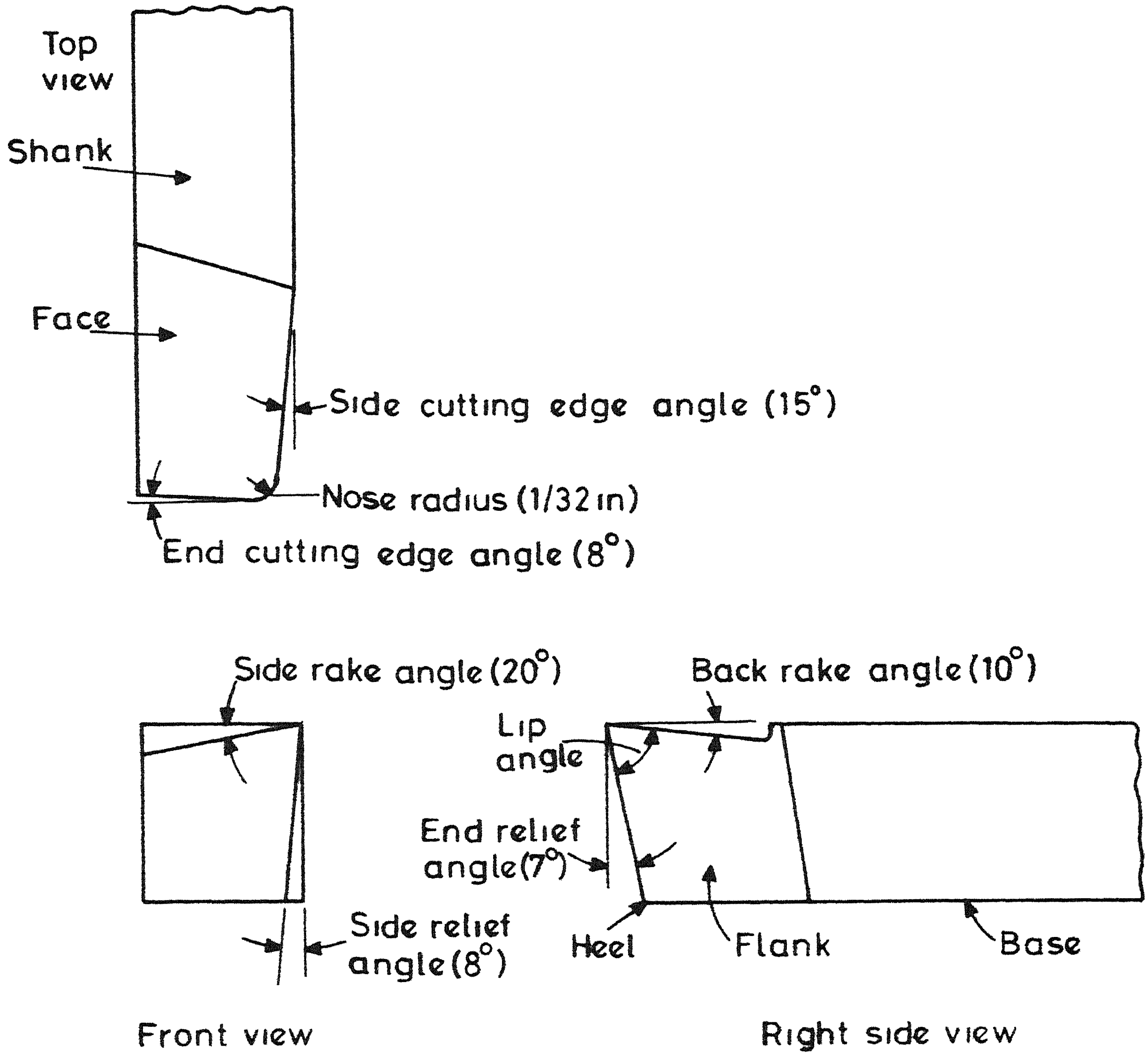


Fig 1.1 A straight-shank right-cut single point tool illustrating the elements of the tool signature as designated by the ASA. Positive rake angles are shown.

rake surface with the auxiliary flank surface. Corner or cutting point is the joining point of principal cutting edge and auxiliary cutting edge. Nomenclature of a single point turning tool is shown in Fig. 1.1.

The orientations of the various tool angles can be stated as below.

i. Back Rake Angle:- This is the angle between the face of the tool and a line that is parallel to the base of the tool holder. It is measured in a plane parallel to the side cutting edge and perpendicular to the base. Variations in the back rake angle affect the direction of chip flow. As this angle is increased while other conditions remain constant, tool life will increase slightly and the cutting force required will decrease. Because continual regrinding of this angle reduces the thickness of the tool its resultant weakening, steep rake angles are usually obtained by alterations in the side rake rather than the back rake angle.

ii. Side Rake Angle:- It is the angle between the tool face and a plane parallel to the base. It is measured in a plane perpendicular to both the base of the holder and the side cutting edge. As the angle is increased reductions in cutting force, increased tool life and improvement in surface finish usually result. Variations in this angle affect the direction of chip flow.

iii. End Relief Angle:- This is the angle between the end flank and a line perpendicular to the base of the tool. The purpose of this angle is to prevent rubbing between the workpiece and the end flank of the tool. An excessive relief angle reduces the strength of the tool, hence the angle should not be larger than necessary.

iv. Side Relief Angle:- This is the angle between side flank of the tool and a line perpendicular to the base. Comments regarding end relief angle are applicable also to side relief angles. For turning operations, the side relief angle must be large enough to allow for the feed-helix angle on the shoulder of the workpiece.

v. End Cutting Edge Angle:- This is the angle between the edge on the end of the tool and a plane perpendicular to the side of the tool shank. The purpose of the angle is to avoid rubbing between the edge of the tool and the workpiece. As with end relief angle, excessive end cutting edges reduce tool strength with no added benefits.

vi. Side Cutting Edge Angle:- This is the angle between the side cutting edge and side of the tool shank. This side edge provides the major cutting action and should be kept as sharp as possible. Increasing the angle tends to widen the chip and influences the direction of chip flow. An excessive side cutting edge angle may cause chatter and should be avoided. As the angle is increased, increased tool life and minor improvement in surface finish can be expected. However, these

benefits will usually be lost if chatter occurs.

vii. Nose Radius:- Nose radius connects the two cutting edges smoothly. Although straight chamfers are sometimes ground to form the nose, most satisfactory results are obtained when the nose is in the form of an arc. Increasing the nose radius avoids high heat concentration at a point. Improvement in tool life and surface finish and a slight reduction in cutting force usually result as nose radius is increased. But chatter will result if the nose radius is too large.

There are many systems to describe the tool geometry Orthogonal rake system and tool signature are the most commonly used systems.

(a) American system or tool signature- it gives all the above mentioned seven parameters in the same order. Angles are specified in degrees whereas the radius in the inch.

$- \alpha\ \beta\ \gamma\ \delta\ \theta\ \emptyset\ r$

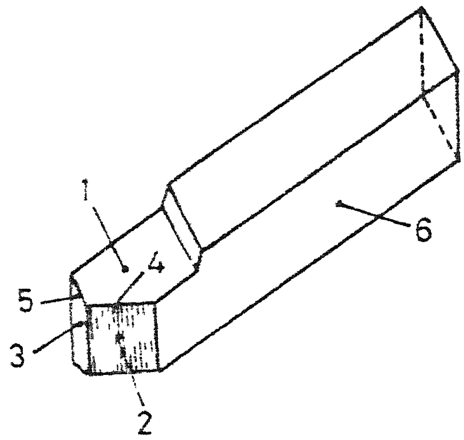
(b) International orthogonal rake system- This system specifies the tool angles in various cross-sections viz.,in the direction of chip flow and in the direction normal to it; as shown in Fig. 1.2.

$\lambda - \alpha_o - \beta_o - \beta_1 - \emptyset_{tr} - \emptyset_p - r$

λ - Inclination angle

α_o - Side or main rake angle

β_o - Side or main relief angle



- Face 2 - Side flank 3 - End clearance face
- Cutting edge 5 - Trailing edge 6 - Body

Fig.1.2(a) Various faces of a single point cutting tool.

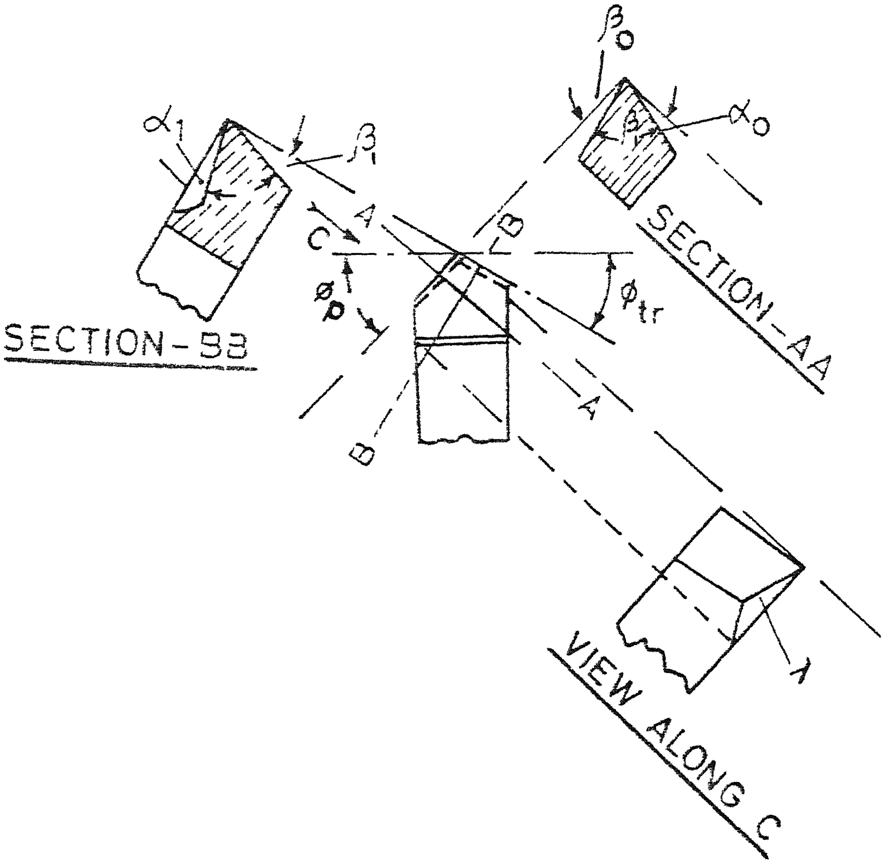


Fig.1.2(b) Various angles defining the tool geometry in international orthogonal rake system.

β_1 -- Auxiliary or end relief angle

ϕ_{tr} - Trail or end cutting edge angle

ϕ_p - Plan approach or entering cutting edge angle.

r - Nose radius mm.

The relationships between tool angles in American system and International orthogonal rake system are given by-

$$\tan \lambda = \tan \alpha . \sin \phi - \tan \beta . \cos \phi$$

$$\tan \alpha_o = \tan \alpha . \cos \phi + \tan \beta . \sin \phi$$

$$\tan \alpha = \tan \alpha_o . \cos \phi_p + \tan \lambda . \sin \phi_p$$

$$\tan \beta = \tan \alpha_o . \sin \phi_p - \tan \lambda . \cos \phi_p$$

$$\cot^2 \beta_o + \tan^2 \lambda = \cot^2 \delta + \cot^2 \gamma$$

$$\cot \delta = \cot \beta_o . \sin \phi_p + \tan \lambda . \cos \phi_p$$

$$\cot \gamma = \cot \beta_o . \cos \phi_p - \tan \lambda . \sin \phi_p$$

The above relations provide means for converting tool geometry from one system to another.

Variations in the shape of the cutting tool influence tool life, surface finish, force required etc. as follows:-

a. Type of chips generated and chip flow direction:

With high rake angles we get continuous chips whereas with low or negative rake angles we get discontinuous chips when other conditions are same. The curling of chip increases with increased angles. The direction of chip flow is governed by the effective rake angle. The chip thickness

ratio is governed by back rake angle.

b. Cutting forces:

Cutting forces are mainly governed by side rake and back rake angles.

c. Heat generated:

Increase in the rake angle reduces the heat generated in shearing, but heat dissipation is also slow because of the reduced area.

d. Tool wear:

Crater tool wear is indirectly affected by rake angle, as type of chips and the temperature play an important role in it. However flank wear is directly affected by end relief angle. Increase in rake, relief, side cutting edge angles and nose radius gives reduced tool wear.

e. Tool life:

1) Rake angle - Increased rake angle results in reduced cutting forces and lesser heat generation and thus improves the tool life. But after a certain value the tool tip weakens.

2) Relief angle- Large relief angles reduce the rubbing and thus give longer tool life.

f. Surface finish:

With increase in nose radius, surface finish increases, but high value may lead to chatter and will give rough surface.

A good design of tool is thus necessary for the best performance of the tool. Apart from the tool geometry the cutting conditions also effect severely the tool performance. Cutting conditions include speed, feed and depth of cut used for machining and the cutting fluid. The tool life which is considered as the most important, is a function of feed, speed and depth of cut. In addition to this the power consumed in metal cutting, surface finish, the forces acting on workpiece also depend on one or all of the above mentioned cutting conditions. Thus careful selection of the cutting conditions is equally important.

1.2 Literature Survey:

The problem of designing a tool for best performance is as old as the metal cutting theory. Due to high complexities involved in the operations on a job and the different kinds of workpiece and tool materials used, it is not possible to give general formulae for designing a tool. However many investigators contributed to the current design procedure by studying effects of tool geometry and cutting conditions on the tool life and the machining cost which are considered as the most important criteria. But even after all these attempts the tool design procedure is still a selection of tool angles from various tables which are based on the investigations. And though the workers agree that the tool life is affected by the tool angles, the tool life constants and indices are not given as a function of tool

angles anywhere. These constants and indices are chosen according to the workpiece-tool combination.

Economics of machining is always of prime importance and hence the cutting conditions are always optimized to satisfy the objective. Minimum machining cost, maximum production rate or maximum profit rate are generally the objectives. As discussed by Bhattacharya [1] many researchers like Bjorke, Bekes, Basu, Colding gave different models for optimization of the cutting conditions. A probabilistic model for determining optimum machining conditions was given by Hati [17].

The chip formation process was studied by many people. Most of them tried to explain the chip curl. Out of these, Rubenstien and Dawe [19] gave a model, treating chip as a plastic beam subjected to bending moment. They obtained expressions for the initial chip radius under free and forced conditions. Nakayama [20] has also done extensive work in analysing the final shape of continuous chip. Nayak and Cook [18] made an attempt to represent the chip by using a graphical method which gives a very close approximation of actual chip shape.

1.3 Objectives

One of the objectives of the present work is to define the surfaces of a single point turning tool mathematically. The main objective is to develop an interactive, user friendly package, to design a single point cutting tool. The package should be such that it can cover all aspects of cutting

tool design. In addition to this it should optimize the cutting conditions for the given set of constraints, so as to give all the geometrical details of a given tool and the operating conditions such as depth of cut feed, speed etc. To facilitate visualization of the tool, formthe designer, the package should provide the orthographic and isometric views of the tool. The package must also give a display of chip formation process in an animated for to facilitate study of machining process without actually doing it. The present work suggests a new methodology for optimization of tool geometry by considering the effect of various tool angles on the constants and exponents in the tool life equation.

1.4 Organisation, Scope and Limitations

a. Organisation: An interactive package is developed to cover all the above mentioned objectives. The package first designs a tool, the optimisation of cutting conditions is used as a part of tool design. Also there is a new methodology suggested for using optimization of tool geometry parameters, which will be more useful and practical for tool manufacturers. After the tool design the package gives a display of orthographic and isometric views of tool. The last part of the package is display of chip formation process in animated form.

b. Scope : This package is an efficient substitution for the long and tedious tool design procedure. The graphic display of tool and the process gives a chance to the designer to

actually observe the tool from different views without actually drawing it. The package gives the optimised cutting conditions for each cut, which thus describes the process completely. The new methodology of optimising the tool geometry parameters may prove very helpful for the tool manufacturers, since it is more important to analyse the tool geometry than analysis or optimising the cutting conditions, for them.

c. Limitations:

1. The material properties vary to a large extent with the composition of the material. Hence for a very accurate model we need to introduce data for all possible combinations and compositions.

2. Not much information is available in the literature about exact coefficients of friction in metal cutting, between such specific work and tool material combinations.

3. The display of the chip formation process in an animated form has its own limitation due to system response time between two frames displayed. Hence it cannot achieve a real time display.

4. The chip breaking is one of the phenomenon in which designer will be interested but due to insufficient data available about exact conditions of chip breaking, it is not possible to introduce chip breaking phenomena in the display of chip formation process.

CHAPTER 2

GEOMETRICAL DEFINITION

2.1 Geometry of a Cutting Tool

Geometry of single point turning tool can be described using many standard systems, the common systems used are International Orthogonal Rake System, Tool-in-hand nomenclature and Tool Signature system. The most simple and convenient is Tool signature system which describes the tool angles and nose radius. It gives numerical values of back rake angle, side rake angle, and relief angle, side relief angle, end cutting edge angle, side cutting edge angle and nose radius respectively (angles specified in degrees and radius in inch). In addition to this we need the dimensions of the tool bit, which come from the actual tool design part, to describe the exact tool geometry.

Analysis of tool shape includes-

a. Locating the cutting edges and

b. Stating the inclinations of the various surfaces

A single point turning tool can be described as a closed volume bound by various surfaces like rake surface, clearance surface, nose cone, chip breaker etc. The tool signature provides all the necessary data describing these surfaces. The various angles provide the inclinations of these surfaces and the dimensions of the tool bit makes it possible to locate the edges.

2.2 Mathematical Model

Mathematical modelling of the tool includes

i. Defining the corner points of the tool and

ii. Defining the surfaces mathematically.

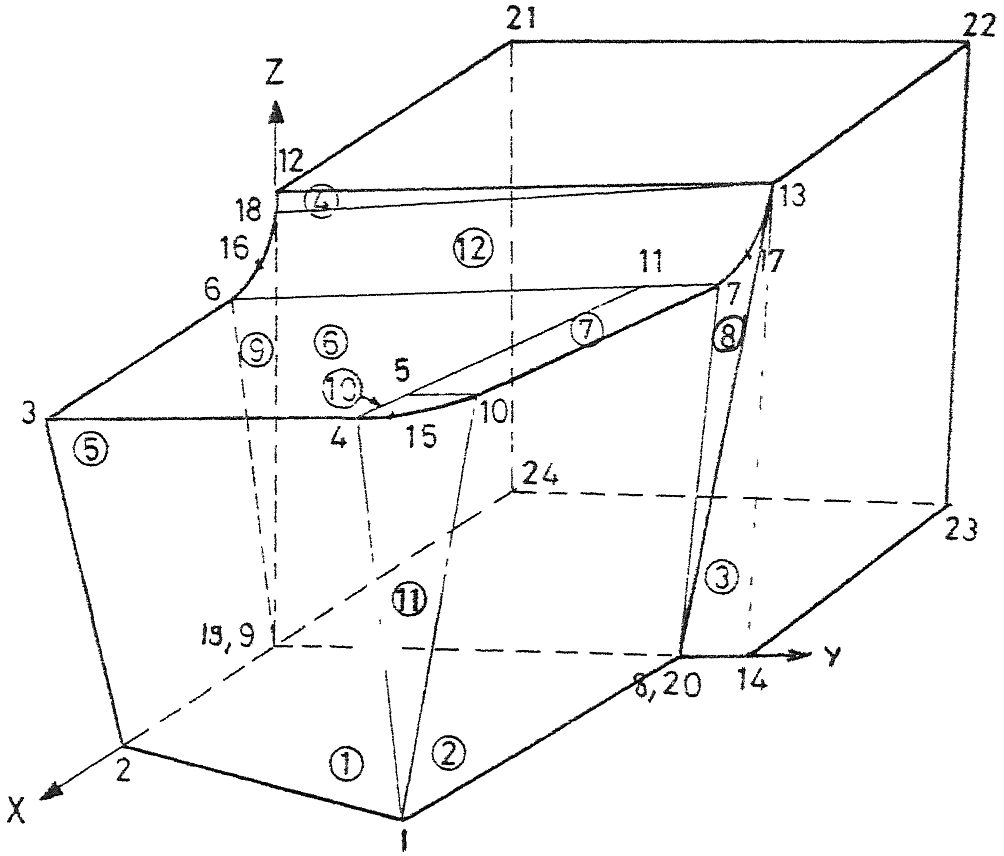
The mathematical modelling describes all the boundary surfaces of the tool. These mathematical equations may be used for programming the numerically controlled machines to generate the tool surfaces.

i. Defining the corner points:

From the design of a single point cutting tool one knows the length, width and height of the tool. Using this information all the corner points of the tool can be defined using a local coordinate system. The coordinate system is assumed to have its origin located at the bottom left corner of the tool bit, with the positive X-direction along the tool from back to front, positive Y-direction along the tool from left to right and positive Z-direction along the tool from bottom to top of the tool. The coordinates of the various corner points shown in Fig. 2.1, in this coordinate system will be as given in Table 1.

ii. Mathematical representation of the tool surfaces:

The tool surfaces can be represented by using various definitions of surfaces or each surface can be considered as a set of such definable surfaces. The surfaces can



g.2.1 Coordinate system corner points and the tool surfaces.

Note: Numbers corresponding to the surfaces are encircled.

<u>TABLE 1</u>

Co-ordinates of various corner points

Point	X	Y	Z
1	L-H tanγ	B- L tan ϕ_1 - H tan∂	O
2	L-B tan θ_1 - H tanγ	O	O
3	L- B tan θ_1	O	-(B-L tan ϕ_1) tan β_1
4	L-r+r.cos ϕ_1	Y(10)-r cos ϕ_1	H- r sin β_1
5	L-r cos β_1 sin θ_1 -r cosα_1 cos ϕ_1	B-r cos β_1 Cos θ_1 - L tan ϕ_1 - r cos α_1 sin ϕ_1	H- r sin β_1 -r sin α_1
6	R_1	O	Z(3)-(X(3)-R_1) tan α_1
7	R_1	B-R_1 tan ϕ_1	H-R_1
8	O	B-H tan ∂	O
9	O	O	O
10	L-r+r sin ϕ_1	B-X(10) tan ϕ_1	H-(r-r sin ϕ_1) tan α_1+r cos ϕ_1 tan β_1
11	R_1	Y(4)+X(4) tan ϕ_1	H-L tan α_1 r.cos θ_1 sin β_1
12	O	O	H

Point	X	Y	Z
13	0	B	H
14	0	B	0
15	$L - r \sin \phi_1$	$Y(10) - r \cdot \cos \phi_1$	H
16	$R_1 - R_1/1.414$	0	$Z(6)+X(16)$
17	$X(16)$	$Y(7)+X(17)\tan \phi_1$	$Z(7)+X(16)$
18	0	0	$H - B \tan \beta_1$
19	0	0	0
20	0	$B - H \tan \partial$	0
21	-20	0	H
22	-20	B	H
23	-20	B	0
24	-20	0	0

be classified into various types such as swept surfaces, lofted surfaces, bilinear surfaces and ruled surfaces as given by Faux and Pratt [3]. Bilinear surfaces have two pairs of straight lines as their boundaries. Ruled surfaces have a straight line as the generatrix and some curve as the directrix. All the tool surfaces can be defined as either one or a combination of these two types.

As shown in Fig. 2.1, surfaces 1 to 7 have been defined mathematically. Since the coordinates of corner points are known, these surfaces have been defined as bilinear surfaces.

$$o \leq u \leq 1 \quad \text{and} \quad o \leq v \leq 1$$

For simplicity write the matrix

$$[(1-u).(1-v) \quad (1-u).v \quad (1-v).u \quad v.u] = [M]$$

a. Surface 1: Corner points 1,2,3,4

$$r_1(u,v) = [M]. \begin{bmatrix} X_3 & Y_3 & Z_3 \\ X_4 & Y_4 & Z_4 \\ X_2 & Y_2 & Z_2 \\ X_1 & Y_1 & Z_1 \end{bmatrix}$$

b. Surface 2: Corner points 1,10,7,20

$$r_2(u,v) = [M] \begin{bmatrix} X_{10} & Y_{10} & Z_{10} \\ X_7 & Y_7 & Z_7 \\ X_1 & Y_1 & Z_1 \\ X_{20} & Y_{20} & Z_{20} \end{bmatrix}$$

c. Surface 3: Corner points 20,13,14

$$r_3(u,v) = [M] \begin{bmatrix} X_{13} & Y_{13} & Z_{13} \\ X_{13} & Y_{13} & Z_{13} \\ X_{20} & Y_{20} & Z_{20} \\ X_{14} & Y_{14} & Z_{14} \end{bmatrix}$$

d. Surface 6: Corner points 3,6,11,4

$$r_6(u,v) = [M] \begin{bmatrix} X_6 & Y_6 & Z_6 \\ X_{11} & Y_{11} & Z_{11} \\ X_3 & Y_3 & Z_3 \\ X_4 & Y_4 & Z_4 \end{bmatrix}$$

e. Surface 4: Corner points 18,13,12

$$r_4(u,v) = [M] \begin{bmatrix} X_{12} & Y_{12} & Z_{12} \\ X_{13} & Y_{13} & Z_{13} \\ X_{18} & Y_{18} & Z_{18} \\ X_{13} & Y_{13} & Z_{13} \end{bmatrix}$$

f. Surface 5: Corner points 2,3,6,9

$$r_5(u,v) = [M] \begin{bmatrix} X_6 & Y_6 & Z_6 \\ X_3 & Y_3 & Z_3 \\ X_9 & Y_9 & Z_9 \\ X_2 & Y_2 & Z_2 \end{bmatrix}$$

g. Surface 7: Corner points 10,5,11,7

$$r_7(u,v) = [M] \begin{bmatrix} X_{11} & Y_{11} & Z_{11} \\ X_7 & Y_7 & Z_7 \\ X_5 & Y_5 & Z_5 \\ X_{10} & Y_{10} & Z_{10} \end{bmatrix}$$

h. Surface 10: This is a ruled surface between point 5 and An arc of circle.

$$r_1(u) = \begin{bmatrix} X_5 \\ Y_5 \\ Z_5 \end{bmatrix} \qquad r_2(u) = \begin{bmatrix} \cos(\frac{\pi}{2} -\alpha)(r \cos u \sin \psi - X_5) \\ \cos(\frac{\pi}{2} -\beta)(r \sin u \sin \psi - Y_5) \\ \cos \alpha \cos \beta(r \cos u -Z_5) \end{bmatrix}$$

$$r_{10}(u,v) = (1-v)\, r_1 + v\, r_2$$

$$= \begin{bmatrix} (1-v)\, X_5 + v \cos(\frac{\pi}{2} -\alpha)\, (r \cos u \sin \psi - X_5) \\ (1-v)\, Y_5 + v \cos(\frac{\pi}{2} +\beta)\, (r \sin u \sin \psi - Y_5) \\ (1-v)\, Z_5 + v \cos \alpha\, \cos \beta\, (r \cos \psi - Z_5) \end{bmatrix}$$

$$0 \leq v \leq 1 \;, \qquad \alpha \leq u \leq \alpha + \frac{\pi}{2}$$

[This must be subjected to a correction, i.e. expressing ψ in terms of α, β, u].

i. Surface 11 : This is also a Ruled Surface between point 1 and arc of the circle.

$$r_1 = \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix} \quad r_2 = \begin{bmatrix} \cos(\frac{\pi}{2}-\alpha) \cdot r\cos u \cdot \sin\psi - X_1 \\ \cos(\frac{\pi}{2}+\beta) \cdot r\sin u \cdot \sin\psi - Y_1 \\ \cos\alpha\cos\beta\,(r\cos\psi - Z_1) \end{bmatrix}$$

$$r_{11}(u,v) = (1-v)\,r_1 + v\,r_2$$

$$= \begin{bmatrix} (1-v)\,X_1 + v\cos(\frac{\pi}{2}-\alpha)\,(r\cos u\sin\psi - X_1) \\ (1-v)\,Y_1 + v\cos(\frac{\pi}{2}+\beta)(r\sin u\sin\psi - Y_1) \\ (1-v)\,Z_1 + v\cos\alpha\cos\beta)(r\cos\psi - Z_1) \end{bmatrix}$$

$$0 \le v \le \frac{\pi}{2} \quad , \quad \alpha \le u \le \alpha + \frac{\pi}{2}$$

The equations for the surfaces of the chip breaker depend on the type of chip breaker used. When only a step is used as chip breaker it becomes a part of tool shank. For the chip breaker shown in the Fig. 2.1 the equations for surfaces 8 and 9 will be similar to surface 10. Surface 12 will be a ruled surface between two arcs and hence both r_1 and r_2 will be similar to r_2 for surface 10.

2.3 Display Considerations:

A designer will definitely prefer to see a pictorial view of the tool he designs, rather than visualising it. This program makes it possible for him. The program first draws schamatic orthographic views of a general single point cutting tool; which gives a clear idea about the

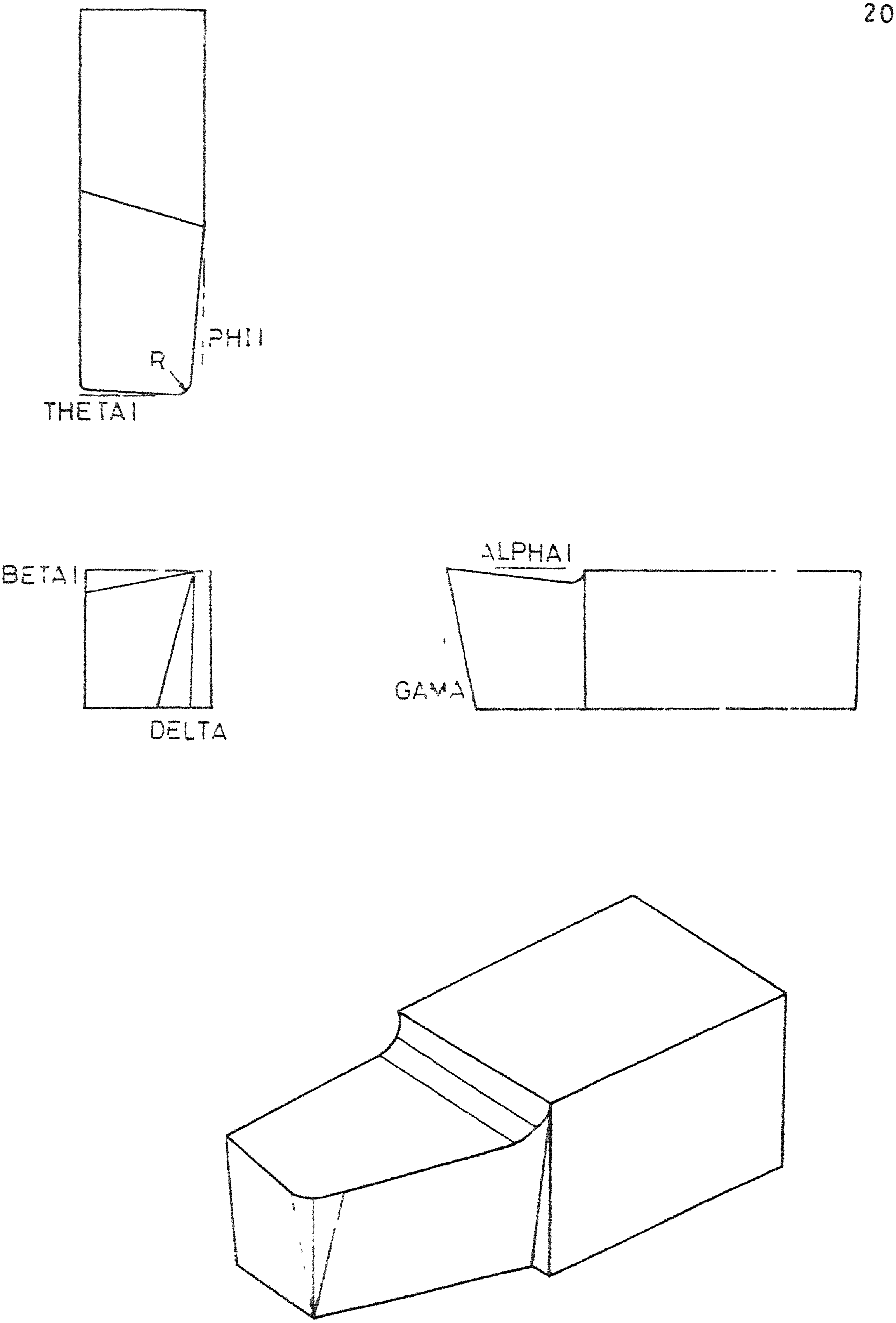


Fig. 2.2 Computer display of various views of the single point turning tool.

various tool angles. It alculates the apperent angles (angles as seen in the orthographic views) made by the tool edges and the coordinates of all corner points. To give the isometric view of the tool, the program multiplies the position vector matrix by a transformation matrix and displays the isometric view. The designer may change the transformation matrix to get any view he wants. This makes it possible for the designer to see all the views of the tool.

CHAPTER 3

OPTIMIZATION OF CUTTING CONDITIONS

3.1 Present Design Procedure

Every process needs a specially designed tool to give optimal results. Same is true for the single point cutting tools. Design of single point cutting tools depends on the work-tool combination, the cutting conditions and the operation to be performed. There are three major steps which are followed for design of a single point cutting tool.

i. Material selection
ii. Selecting the cutting conditions
iii. Deciding the geometry of the tool.

i. Material Selection:

The material selection involves selection of workpiece and tool material. The workpiece material is genera-lly known. But for selecting the tool material there are many factors which are to be considered. For example strength and hardness of the material relative to the workpiece materia The most satisfactory tool material will not necessarily be the one that gives the longest tool life, factors like grinda-bility, tool material cost and the practical levels of cutting

speeds and feeds play important roles in the selection of the best tool material.

High speed steel is most commonly used and it cuts majority of metals efficiently and its toughness makes it particularly more suitable for shock and impact conditions. But these tools are unsuitable for materials with hardness more than 375 BHN. Usually H.S.S. tools are used for cutting speed from 40 to 100 fpm.

Cemented carbide tools have high red hardness and resistance to abrasion. They have low thermal expansion and higher value of thermal conductivity. Used for speeds between 200 to 1500 fpm.

Ceramics tools permit high cutting speeds and can cut materials which are too hard for other tools. It has high hardness, wear resistance and resistance to high temperature, oxidation corrosion, but poor thermal conductivity and thermal shock resistance. Cutting speed upto 1800 fpm is possible.

ii. Selecting the cutting conditions:

Cutting conditions have commanding effect on the performance of the tool, hence it is essential that their selection should be appropriate. The cutting conditions required change with tool-workpiece combination and the nature of the operation to be performed. Cutting conditions include the

following-

1. Depth of cut: Depending on the amount of the metal to be removed and the tool-workpiece properties,the depth of cut is decided. With increased depth of cut machining time decreases but tool life also decreases.

2. Feed : Amount of metal to be removed and tool-workpiece properties govern selection of feed also. But if a range of depth of cut is chosen there is a range of feed which suits best, because feed and depth of cut together decide the amount of metal removed per revolution. Feed governs surface roughness also. With increased feed the surface roughness also increases.

3. Speed: Speed is the main governing factor for tool life and hence is the most important of the cutting conditions. Though machining time decreases with increase in speed, the tool life decreases very fast with increase in speed.

Depending on the various constraints on feed, speed and depth of cut and the objective as maximisation of the production rate or minimsation of cost the cutting conditions are optimized. The constraints of the optimization are like tool deflection permissible, power, torque available, surface finish, tool life etc.

(Discussed Separately).

4. Cutting Fluid: The cutting fluids are mainly used for getting any one or more of the following effects-

a. Cooling b. Lubrication c. Antiwelding effect.

It helps in heat dissipation from the cutting zone. The lubrication between the chip and tool reduces the friction and hence the heat generation. Sulphur, Chlorine etc. are added to the cutting fluids to avoid welding in metal to metal contact region. A wide range of cutting fluids is available but the selection mainly depends on the workpiece-tool combination.

iii. Deciding the geometry of the cutting tool: This is the most important part of the cutting tool design. Geometry of the tool includes all the tool angles, radius and chip breaker. Dimensions of the tool shank and the angles influence the cutting process to a considerable extent, hence tool has to be carefully designed.

1. Tool shank design : After optimization of the cutting conditions the feed, speed and depth of cut for a particular operation are known. Thus tangential, radial and axial components of the cutting force can be calculated. There are various methods for calculating these forces. The two methods discussed by Bhattacharya [1] are -

a. The cutting forces under condition of other variables kept constant, are direct functions of feed (s) and depth of cut (t). The forces can be calculated using the expressions-

$$P_x = C_x t^{xx} S^{yx}$$

$$P_y = C_y t^{xy} S^{yy}$$

$$P_z = C_z t^{xz} S^{yz}$$

where C_x, C_y, C_z and the exponents depend on the work material.

b. Using Granovsky's empirical law for cutting force evaluation, according to which the cutting forces are affected by the various cutting variables e.g. depth of cut, feed, tool geometry, cutting speed, tool wear, hardness of the workpiece material etc. Taking into account the effect of these cutting variables on the forces, an empirical equation is given as follows-

$$P_{(x,y,z)} = [C\ (K_\alpha . K_\phi . K_v . K_r . K_{hf} . K_{cf} . K_m)\ (BHN)^m . t^p, S^q]_{(x,y,z)}$$

where the constants take into account the effects of material, rake angle, side cutting edge angle, speed, nose radius, tool wear, cutting fluid and material transfer respectively. After calculation of P_x, P_y, P_z tool shank can be designed either for maximum permissible tool deflection or for strength and rigidity.

For maximum permissible tool deflection-

$$H = \left(\frac{4 P_z L_e^3}{0.8\,\Delta . 0.8 E}\right)^{0.25}$$

where

- H - Height of the tool
- L_e - Tool overhang
- Δ - Tool deflection permissible
- E - Young's modulus

For rigidity and strength ·

$$\sigma = \frac{6P_z\ L_e}{B.H} \left(\frac{0.4}{B} + \frac{1}{H} \right)$$

where σ – permissible stress of shank material

width of tool is generally taken as 0.6.H
Sometimes shank is designed for one condition and checked to satisfy the other condition also.

2. Rake angle : Tool with large rake angle is weak and tool point may break off. Heat is not conducted readily in such tools, but with decrease in rake angle the cutting force required increases; and thereby the power consumption is more. With increase in rake angle tool life increases initially but after a certain limit it decreases because of the weakening of the tool. But this optimum value varies with work-tool combination and ultimate strength of work material. Bhattacharya[1] has given an empirical equation for the optimum rake as a function of ultimate strength of work material.

$$\alpha_{opt} = \frac{25X10^4}{\sigma_u^{8.0}} \quad \ldots\ldots \text{ For materials with } \sigma_u < 80 \text{ Kg/mm}^2$$

$$\alpha_{opt} = \frac{5X10^{16}}{\sigma_u^{8.0}} \quad \ldots\ldots \text{ For materials with } \sigma_u > 80 \text{ Kg/mm}^2$$

but there is clearly a discontinuity at σ_u =80 Kg/mm^2 which cannot be explained., **and such gross expressions can never yield desired effectiveness.**

3. Side rake angle: Power consumption decreases with increase in side rake angle, same is true with the heat generated. Surface finish improves with increase in side rake angle, but at the same time tool strength decreases.

4. Clearance angle : Increased clearance angle reduces the tool wear and hence improves the tool life. But at the same time the area of heat dissipation and tool strength decreases. Optimum clearance angle varies with the feed.

5. Cutting edge angle: Tool life improves with increased cutting edge angles but large angles cause chatter and hence the maximum values are governed by chatter conditions.

6. Nose radius: Tool life increases with nose radius but large nose radius causes chatter.

Chip breaker design : Depending on the depth of cut used, the chip breaker width and radius are decided, to give effective breaking.

3.2 Optimum Conditions of Metal Cutting:

i. Objective function: To optimize the cutting conditions (feed, speed and depth of cut) first the objective function is chosen. There are several objective functions proposed but we consider the two of major importance.

1. Maximization of production rate :

$$P_R = \frac{1}{t_1+t_c+t_d\left(\frac{t_c}{T}\right)}$$

2. Minimization of cost :

$$C' = K_1 \; [t_1 + t_c + t_d (\frac{t_c}{T})] + K_2 \; (\frac{t_c}{T})$$

P_R - Production rate

C' - Cost of machining per component

K_1 - Overall operating cost

K_2 - Tool costs per cutting edge

t_1 - Idle time

t_c - Cutting time

t_d - Tool changing time

T - Tool life

ii. Constraints in the optimization :

For optimization of the cutting conditions the constraints on them are to be considered first. The restrictions imposed are similar to that stated by Bjørke.

a. Power constraint : The power absorbed by the cutting process can not exceed the power capacity (N_m) of the main drive.

$$\frac{P_z V}{6110} \leq N_m \; \eta$$

$$P_z = C_z \; t^x S^y V^\lambda$$

$$\therefore \quad S^y \; t^x D^{\lambda+1} \; N^{\lambda+1} \leq \frac{N_m . \eta . 6110 \; 1000^{\lambda+1}}{\pi^{\lambda+1} \; C_z} = B_1$$

b. Torque constraint: T rque absorbed by the cutting processes must not exceed tarque capacity of the main drive (m_d)

$$\frac{P_z D}{2} \leq M_d.$$

$$\therefore \quad t.s.\ N^{\lambda}\ D^{\lambda+1} \leq \frac{2000\ .\ 1000^{\lambda}\ .\ M_d}{C_z\ \pi^{\lambda}} = B_2$$

c. Maximum permissible workpiece deflection constraint:

The workpiece deflection should not exceed the maximum permissible deflection value.

$$\Delta = \frac{P_y\ L^3}{m\ E.I}$$

$$P_y = C_y\ t^x s^y V^{\lambda}$$

$$\therefore \quad s^y\ t^x D^{\lambda-4}\ N^{\lambda} \leq \left(\frac{1000}{\pi}\right)^{\lambda} \frac{m.\pi.\Delta.E}{C_y.64.L^3} = B_3$$

L- Length of workpiece

m- Constant depending on type of workholding

d. Bounds on the cutting speed: Lower bound on cutting speed is provided by the built up edge formation criteria, whereas the upper bound is provided for the operator safety.

$$V_{min} \leq V \leq V_{max}.$$

$$\therefore \quad ND \geq \frac{1000\ .V_{min}}{\pi} = B_{42}$$

$$ND \leq \frac{1000.V_{max}}{\pi} = B_{41}$$

e. Bounds on the feed: Lower bound on feed is needed because too low feed will increase the machining time. Upper bound is to provide good surface finish.

$$s_{min} \leq s \leq s_{max}.$$

f. Bounds on the depth of cut: Lower bound restricts the number of passes required to finish the machining. Upper bound is needed to avoid the problems of vibration.

iii. Program structure: The program gives a multistage optimization of the cutting conditions, using interior penalty function method with Davidon-Fletcher- Powell method of unconstrained minima[11], the algorithm is given below.

1. Initialisation
2. Diameter =Initial Diameter
3. Set Diameter = Diameter-2* Depth of cut
4. If (Diameter-Final Diameter)/2.0 > T_{max}, then

   Calculate current values of speed, feed and depth of cut

   Go to step 9

   else,

   T_{max} = (Diameter-final Diameter)/2.0

5. If ((Dimeter-final Diameter)/2.0)-0.01 > T_{min}, then

   Calculate current values of speed, feed and depth of cut

   Go to step 9

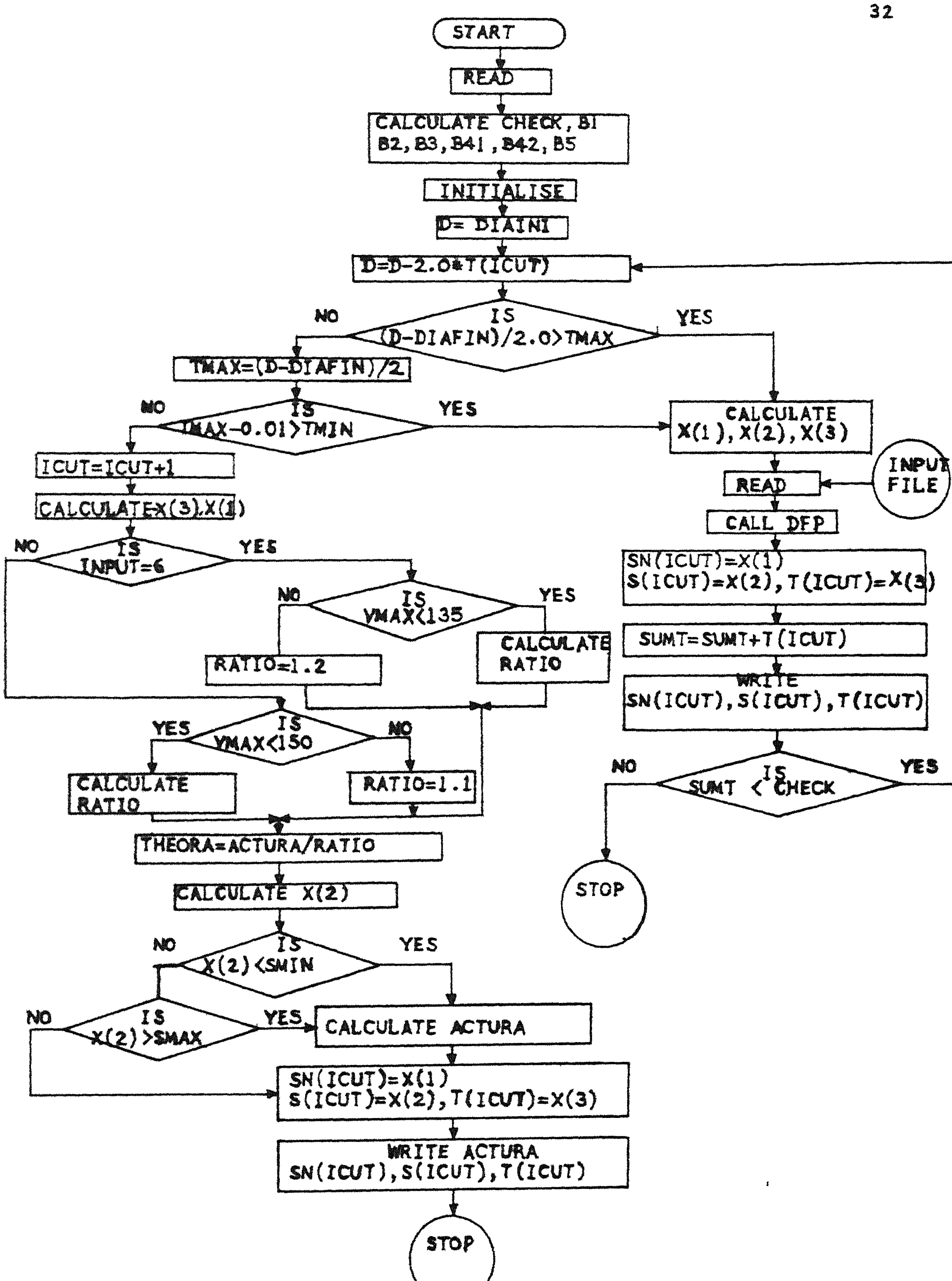


FIG. 3.1 FLOW CHART FOR MULTISTAGE OPTIMIZATION OF CUTTING CONDITIONS.

else

Number of cut is increamented by 1

Calculate current values of depth of cut and speed.

6. If workpiece material is cast iron or wrought iron then,

If V_{max} < 150 then

Calculate ratio of theoretical and actual surface finish

Go to step 7

else

Ratio = 1.1

Go to step 7

else

If V_{max} < 135 then

Calculate Ratio

Go to step 7

else

Ratio = 1.2

7. Theoretical surface roughness = Actual roughness/Ratio

Feed = SQRT (Theoretical roughness * Radius/0.0321)

8. If feed < s_{min} then

Print message

Stop

else

Assign current values of speed, feed and depth of cut as values for this cut

write the values

Stop

9. Read input file .

10. Call optimization subroutine.

11. Assign current values of speed, feed and depth of cut as values for this cut .

12. Sum of the depth of cuts is increamented by the current value of depth of cut.

13. Write values of speed, feed and depth of cut for the present cut.

14. If sum of the depth of cuts < (Initial diameter - Final diameter)/ 2.0 Then

Go To Step 3

else

Stop

End.

3.3 Computations of Forces, Power and Surface Finish:

i. Force Computations: The axial, radial and tangential forces (P_x,P_y,P_z) acting on workpiece during machining with a single point cutting tool are calculated using Granovsky's empirical law for cutting forces.

$$P_{(x,y,z)} = [C\ (K_\alpha . K_\phi .\ K_v . K_r\ K_{hf} . K_{cf} . K_m](BHN)^m\ t^p s^q]_{(x,y,z)}$$

The values of constants are selected from the tables. (Appendix)

ii. Power Consumption : Power consumed during machining is calculated as follows

$$\text{Power} = \frac{P_z . V}{6110}$$

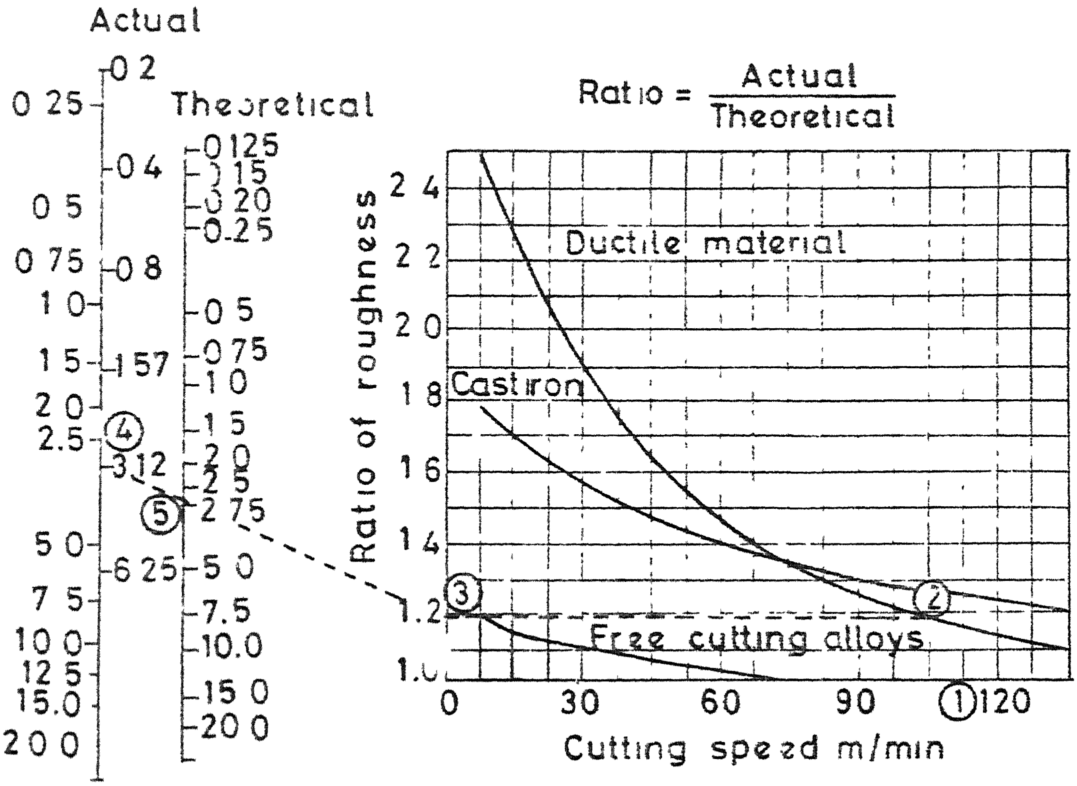


Fig. 3.2 Nomogram for determining the probable surface finish depending on the employed feed and nose radius.

iii. Surface Roughness: Theoretical surface roughness is calculated by using the expression

$$R_a = \frac{0.0321\ s^2}{R}$$

knowing the work material and the speed of machining the ratio of actual finish to theoretical surface finish can be found out using Fig. 3.2.

Actual surface finish = Theoretical surface finish x Ratio.

CHAPTER 4

OPTIMIZATION OF TOOL GEOMETRY

4.1 Effect of Tool Geometry:

From the literature survey it is clear that the tool geometry parameters affect the tool life, and it is an accepted fact. But in all the optimization methods which have been carried out for optimal cutting conditions, the parameters and the exponents of tool life equation are assumed to be constant. Irrespective of the geometry the same exponents are generally used to calculate the tool life. This indicates that the change in the tool life equation with tool geometry has never been given importance.

The effect of various tool geometry parameters can be stated as follows [1,4].

a. Rake angle : With the increased rake angle the forces required to cut the material decrease, so does the heat generated. This improves the tool life. But weakening of tool with increased rake angle limits the upper value of rake angle.

b. Clearance angle: With the increased clearance angle the flank wear decreases and hence tool life improves but it is the weakened tool which decreases the tool life after some particular value.

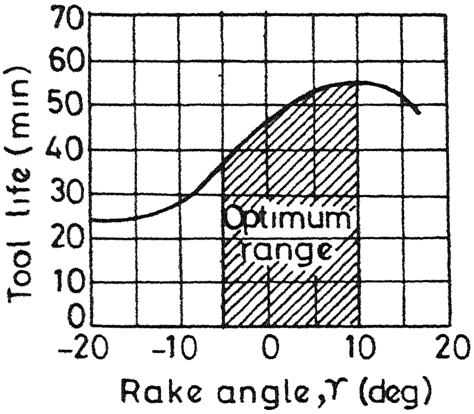


Fig. 4.1 Effect of rake angle on tool life (V = 98 f.p.m work piece material: 18-8 steel; tool: carbide)

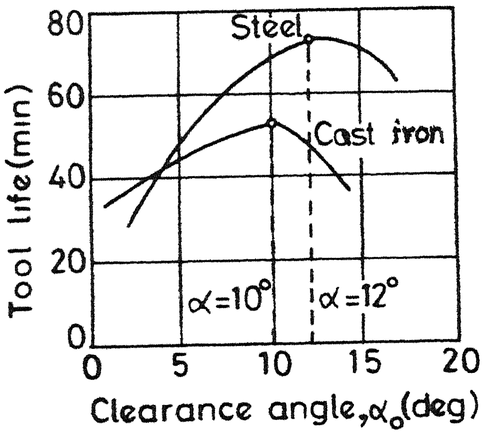


Fig. 4.2 Effect of work material on optimum clearance angle selection for maximized tool life.

c. Side cutting edge angle: Larger the side cutting edge better is the tool life but too large an angle causes chatter. Hence the limiting value is given by chatter conditions.

d. End cutting edge angle: As the end cutting edge is increased the surface roughness increases, and with decrease in end cutting edge angle the radial component of cutting force (p_y) increases thus causing chatter if workpiece is not sufficiently stiff.

e. Nose radius: Larger the nose radius better the surface finish but too large values cause chatter if workpiece is not sufficiently stiff.

After a careful study of the available literature about tool geometry and its effect on the tool life and other conditions like chatter etc., a methodology is suggested, for optimization of the tool geometry. Though all the available literature shows the effect of these geometric parameters on the tool life, it is not the tool life as a whole which is affected by the tool geometry. Because of the fact that the speed, feed and depth of cut are assumed to be constant when we study the effect of change in tool angles on the tool life, it indicates the effect on the exponents and the constant of tool life equation. Sometimes the speed for a constant tool life is plotted for changing tool geometry. But it just shows how much the speed will change to compensate the

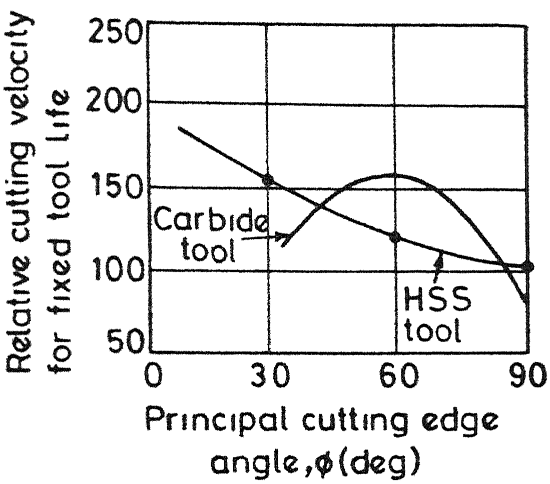


Fig. 4.3 **Effect of the principal cutting edge angle, φ on the cutting velocity for a fixed tool life.**

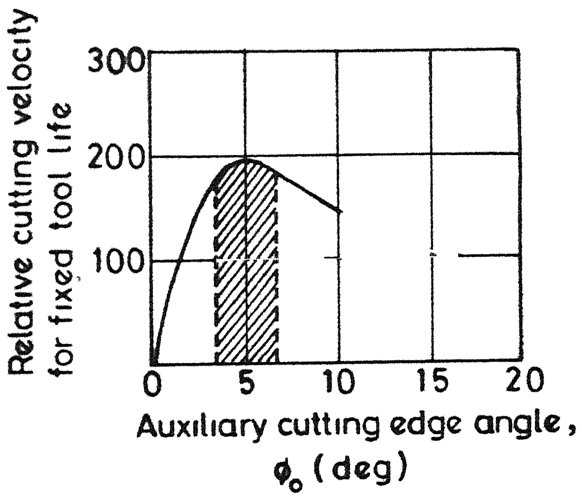


Fig. 4.4 **Effect of the auxiliary cutting edge angle, ϕ_o on the tool life characteristic.**

effect of the tool geometry changes on the tool life. It is clear that in the tool life equation where cutting conditions are constant for the investigations being made, it is the constant and the exponents which are being affected by changes in the tool angles. Thus the try is to express these quantities as a function of tool geometry, which will thus give the effect of tool geometry on the tool life for any particular combination of the tool angles.

Assumptions made are:

1. Effect on the exponents of feed and depth of cut is neglected as their contribution to the total tool life is very small, compared to other factors and there is no data available which clearly indicates the effect of tool angles on the relation of feed and depth of cut with tool life.

2. Equal weightage is given to individual effect of all angles on the tool life constant.

3. The analysis is more qualitative than quantitive and the part of the tool life constant which considers the effect of other parameters like material etc. is not considered in this analysis.

4. The analysis is for normal rake system.

i. Effect of the rake angle: The Figure 4.1 shows a graph of tool life against rake angle. The curve shown can be represented as a mathematical expression by using curve

fitting techniques. The equation which the curve assumes is a sinusidal curve equation. The left side of the expression is tool life.

$$\left(\frac{C}{V}\right)^{1/n} = f(\alpha)$$

But it is clear from the experiments done by Kronenberg [12], that the exponent of the tool life equation is not affected by the change in rake angle. Thus an equation representing C as a function of rake angle (α), is obtained

$$C = V.\ \left(16 \sin\left(\frac{(\alpha+5)\pi}{30}\right) + 39\right)^{n}.$$

The cutting conditions were as follows:

Work Material	- 18.8 steel
Tool	- Carbide
V	- 98 m/min .

ii. Effect of clearance angle : The expression developed by A. Ghosh [16] for study of the tool wear gives a relation between tool life and clearance angle. Careful study of the equation shows that the equation assumes a form $VT^n=C$ and the right hand side thus represents C. Thus an expression for C a function of the clearance angle is obtained

$$VT^{0.8} = \left[\frac{4.\tan\gamma}{5z_o^*}\right]^{0.8}.h_f.A^{-0.6}$$

where z_o^*, h_f, A are constants.

$$\therefore\ C = K_1\ (\tan\gamma)^{0.8}$$

iii. Effect of side cutting edge angle: Bhattacharya [1] has stated an equation which gives effect of side cutting edge angle on the tool life.

$$VT^{0.11} = 78\ (\phi + 15)^{0.264}$$

ϕ - side cutting edge angle.

Here also the case is same as discussed above and the constant C can be roughly expressed as

$$C = 78\ (\phi + 15)^{0.264}$$

The cutting conditions were as follows:

Work Material	-	SAE 2345 annealed steel forging
Tool	-	H.S.S.
Back Rake	-	8^{o}
Side Rake	-	14^{o}
Nose radius	-	3/64 in.
Feed	-	0.0125 in./rev.

iv. Effect of end cutting edge angle: From the graph shown in Figure 4.4 by using curve fitting techniques, tool life can be expressed as a function of end cutting edge angle as

$$T = \left(\frac{C}{V}\right)^{1/n} = 100 + (91.8\ \theta - 99.8)\ e^{-0.256\ \theta}$$

Thus we have an expression in which both C and n are variables. Due to insufficient data we cannot make any assumption, but with some more data we can definitely express these variables

as a function of θ.

But actually for both cutting edge angles the maximum values are governed by chatter conditions.

Though the cutting conditions in the above mentioned cases are different, the data is used for developing the methodology because basic nature of the curve remains the same though the values may change. Due to unavailability of data giving the set of above mentioned graphs under identical conditions, it was not possible to give exact expressions for the parameters. With special experiments, carried out under identical conditions to give the necessary data, the results will be more accurate.

4.2 Formulation of the Objective Function:

For a given set of cutting conditions (speed, feed and depth of cut) if we want to optimize, the tool geometry, the problem can be formulated by taking maximization of production rate as our objective function.

$$P_R=1/\ (t_1+t_c+t_d(\ \frac{t_c}{T}))$$

Thus after simplification we get maximization of the tool life as our objective function, as other terms in the above expression are independent of the tool geometry parameters.

Since values of cutting edge angles are governed mainly by the chatter condition, the values of these can be directly obtained and even if these values are used as constrain

and optimize the objective function, the result will be the same. But to take into account the effect of side cutting edge on the constant of tool life equation, which will be definitely affected and thus the combination of other two parameters will also be affected. So proper weightage is given to side cutting edge angle in the objective function. The values of $C^{1/n}$ which are obtained from the corresponding primary equations, are used in the objective function. The three angles discussed above are given equal weightage and to make it sure that if some parameter makes the tool life zero, the tool life should be zero irrespective of the values of other parameters, multiplying all these three subparts and taking cube root to give a qualitative expression corresponding to $C^{1/n}$. The objective function is thus

$$T=[(7\beta^{9.09}.(\varnothing+15)^{2.4}.\ K_1{}^{1/0.8}.\ \tan\gamma.(16\sin(\frac{(\alpha+5)\pi}{30})+39)29.7]^{1/3}$$

$$[V^{-1}.s^{-K_2}\ t^{-\ 3}]^{1/n}.K_4$$

where

K_1, K_2, K_3 and K_4 are constants.

In addition to the geometric parameters the material properties also affect the constant of tool life equation. Hence the constant K_4 is introduced which will depend on the work material used. From the objective function it is clear that the cutting conditions are treated as constant and they will not affect the objective of the optimization. So the objective becomes maximization of the first

part of the equation stated above. Though the cutting conditions do not affect the objective function, the constraint on side cutting edge angle is affected by the value of depth of cut used. Since the limitation is of maximum width of cut (b_{max}) which is a function of depth of cut.

$$b_{max} = \frac{t}{\cos \phi_{max}}$$ Thus the constraint will be-

$$1 \leq \phi \leq \phi_{max}$$

4.3 Constraints:

The limiting values of the angles which are known from the practical conditions are used as the constraints.

$$-20 \leq \alpha \leq 20$$

$1 \leq \gamma \leq 25$ (Since zero clearance angle means zero tool life)

The constraint on the value of side cutting edge angle is governed by the chatter conditions. The limiting value thus can be calculated using the chatter conditions, using the equation-

$$1/b_{max} = -1.6 \quad u. \sqrt{1+(F_x/F_y)^2}. (\lambda_{uu} \cos \beta_c \cos \gamma_c - \lambda_{uv} \sin \beta_c \sin \gamma_c)$$

where

b_{max} = Maximum width of cut permissible

u = energy per unit volume

$\lambda_{uu}, \lambda_{uv}$ - real parts of motion in u direction, due to forces in u and v directions. respectively.

β_c, γ_c - angles made by u with force difference vector and x-axis respectively.

From the value of b_{max} the limiting value of side cutting edge angle can be calculated using the value of depth of cut used.

$$b_{max} = \frac{t}{\cos \emptyset_{max}}$$

The value of b_{max} is taken as 2 mm for the current problem.

4.4 Optimization:

The objective function is optimized by using Interior Penalty Function Method with Davidon-Fletcher -Powell method of unconstrained minima, as given by Rao [11] . To convert the maximization problem to minimization, the objective function is assigned a negative sign.

For optimization of geometrical parameters, though the values of speed, feed and depth of cut used in the present

case are some particular values, it is more practical to consider ~~the~~ the ranges of speed, feed and depth of cut in which the tool will be used. The distribution can be assumed to be normal. The optimization the should be done using stochastic programming.

After the optimization we get values of normal rake angle and normal clearance angle. The values of back rake, side rake, end clearance and side clearance angles can be obtained from these values using the relations-

$$\tan \beta = \tan \alpha_o \cos \phi - \tan \lambda \sin \phi$$

$$\tan \alpha = \tan \alpha_o \sin \phi + \tan \lambda \cos \phi$$

$$\cot \gamma = \cos (90-\phi) \cot \beta_o + \sin (90-\phi) \tan \lambda$$

$$\cot \delta = \sin (90-\phi) \cot \beta_o - \cos (90-\phi) \tan \lambda$$

CHAPTER 5

COMPUTATIONAL ASPECTS

5.1 Block Diagram:

Fig. 5.1 shows the flowchart of the program developed for the design of single point cutting tool for optimal results. In the figure various stages of the analysis have been shown inside rectangular boxes, where as input required at various stages and the results obtained have been encircled. Options available at various stages of the program are at the bottom of the rectangular boxes. Output variables of final interest are power consumed, surface roughness, tool life, all the tool angles and height and width of the tool.

5.2 General Conventions Used in the Program:

Assumptions about the type of input and output variables and units used are given below:

1. Except angles which are easier to visualize in degrees, all the input variables are to be specified in MKS units.
2. All the variables are assumed to be real numbers.
3. The coordinate frame used has positive X-axis from left to right and positive y-axis from top to bottom of the screen.

5.3 Design of Single Point Turning Tool:

The major steps in the program given for design of single point cutting tool are given below. Comments printed on the screen by the computer are given in block capitals. The explainations are given in square brackets. The input variables are assumed to be format-free and are underlined in the example given.

1. Selecting the workpiece material
2. Selection of the tool material
3. Defining the arrays for workpiece and tool properties, coefficient of friction (both for dry and lubricated conditions)
4. Selection of cutting fluid from the recommended fluids
5. Defining the arrays for maximum and minimum speeds
6. Selecting the option of feed or depth of cut range to be chosen
7. Selecting the maximum and minimum values of the feed or depth of cut, as the case may be
8. Deciding the range of the other quantity from the chosen range
9. Defining arrays for the tool life contant and exponents for both dry as well as coolent conditions
10. Read values of tool overhang and permissible tool deflection
11. Multistage optimization of cutting conditions(feed,speed and depth of cut for each cut) using various constraints

such as permissible tool deflection, power available, torque available, minimum and maximum feed, speed and depth of cut possible, minimum tool life and surface finish required. (This is a separate program, but can be called in the main program as a subroutine)

12. Calculation of tool life for the mean cutting speed

13. Defining arrays for the tool geometry (all angles and nose radius)

14. Assigning values of tool angles, depending on the tool-workpiece combination

15. Assigning value of nose radius, depending on the depth of cut

16. Designing chip breaker, depending on the depth of cut

17. Calculation of the theoretical surface finish possible

18. Calculating the ratio of theoretical and actual surface finish depending on the work material and speed.

19. Calculation of actual surface finish

20. Defining various constants which give effect of side cutting edge, speed, nose radius, cutting fluid, material, workpiece hardness, feed and depth of cut on the forces P_x, P_y, P_z. (One more method is also given which can be used as an alternative method)

21. Calculation of the forces P_x, P_y, P_z

22. Calculation of the power consumption

23. Tool shank design for the tangential cutting force as well as for the maximum permissible tool deflection and selecting the safer of the two designs.

24. Displaying orthographic views of a general single point turning tool and isometric view of the designed tool.

25. Display of the chip formation process with the designed tool in an animated form as per the option of moving workpiece or moving tool.

5.4 Example:

SELECT WORKPIECE MATERIAL

1. FREE MACHINING STEELS
2. LOW ALLOY STRUCTURAL STEELS
3. STAINLESS STEELS
4. H.S.S.
5.
6. CAST IRON
7. WROUGHT IRON
8. MAGNESIUM AND ALLOYS
9. ALUMINIUM AND ALLOYS
10.
11. COPPER AND ALLOYS

1

[INPUT =1]

SELECT TOOL MATERIAL

1. HIGH SPEED STEEL

2. CARBIDES

3. CERAMICS

1

[INPUT =1]

RECOMMENDED FLUIDS:

SELECT THE CUTTING FLUID FROM THE FOLLOWING

1. 4.L.D. CUTTING FLUID

2. 3.H.D. WATER MISCIBLE

3

[NFLUID =3]

WHICH RANGE YOU WILL LIKE TO CHOOSE?

1. FEED

2. DEPTH OF CUT

2

[CHOICE =2]

CHOOSE MINIMUM AND MAXIMUM DEPTH OF CUT

DEPTH OF CUT BELOW 0.4 RECOMMENDED ONLY FOR CARBIDES

MINIMUM	MAXIMUM
1:0.1	1:0.4
2:0.4	2:2.5
3:2.5	3:4.5
4:4.5	4:10.

2 3

[[illegible]-2, TC[illegible]K2=2]

[Program selects the values

Minimum depth of cut = 0.4

Maximum depth of cut = 2.5

Minimum feed = 0.125

Maximum feed = 0.375

Maximum Speed=VMAX1(INPUT, SCHEK1)=105.0

Minimum speed=VMIN1(INPUT, SCHEK2)= 50.0

Workpiece hardness= W(INPUT,1)=270.0

Shear strength of workpiece=W(INPUT,2)=33.75

Young's Modulus=W(INPUT,4)=21000.0

Tool hardness=TL(INPUT,1)=270.0

Bending strength of tool=TL(IPUT,2)=75.0

Young's Modulus (Tool)=TL(IPUT,4)=21000.0

Coefficient of friction=OIL(INPUT,IPUT)=0.8

Tool life constant and exponents-CV=78.28,XV=0.25,YV=0.33

Exponent =0.147]

PLEASE FEED THE VALUES OF:

PERMISSIBLE TOOL DEFLECTION

TOOL OVERHANG

0.04 15

[DFLECT=0.04,LE=15]

[Optimization of cutting conditions or tool geometry if called]

[The program takes the values of various constants for calculating P_x, P_y, P_z as:

KPHIZ=1.08	KPHIY=1.63	KPHIX=0.70
KVZ=0.91	KVY=0.78	KVX=0.78
[illegible]	KRY=0.61	KRX=1.11
KHF=0.90	KM=1.0	
CMZ=3.57	CMY=0.0027	CMX=0.0212
MZ=0.75	MY=2.0	MX=1.5
DEPTHZ=1.0	DEPTHY=0.9	DEPTHX=1.2
FEEDZ=0.75	FEEDY=0.75	FEEDX=0.75]

PX= 29.618530 Kg

PY= 63.512680 Kg

PZ= 95.869995 Kg

POWER= 1.412160 KW

SURFACE ROUGHNESS= 0.003347 MM

TOOL LIFE= 46.23158 MIN

HEIGHT OF THE TOOL= 9.0058997 MM

WIDTH OF THE TOOL= 5.403538 MM

BACK RAKE ANGLE=12.0

SIDE RAKE ANGLE=12.0

SIDE CUTTING EDGE ANGLE=15.0

END CUTTING EDGE ANGLE=15.0

SIDE RELIEF ANGLE=5.0

END RELIEF ANGLE=5.0

NOSE RADIUS=0.75 MM

CHIP BREAKER WIDTH=2.0 MM

CHIP BREAKER RADIUS=0.5MM

FEED SOME NUMBER FOR DISPLAY OF TOOL VIEWS

5

[KIT=5]

[Display of orthographic views and isometric view of tool]

FEED SOME NUMBER FOR DISPLAY OF CHIP FORMATION PROCESS

6

[KIT=6]

CHOOSE ONE OF THE FOLLOWING

1. MOVING TOOL

2. MOVING WORKPIECE

1

[MIT=1]

GIVE VALUES OF XTIP YTIP CHECKLENGTH SAMPLE LENGTH

INITIAL CHIP RADIUS

45 75 70 1 4

[Display of the chip formation process with moving tool and stationary workpiece].

CHAPTER 6

CHIP MODELLING

6.1 Theory of Chip Modelling:

i. Chip Curl: In the metal cutting process the material is removed in the form of chips. Many writers and researchers have studied [19,20] the mechanism of chip formation; and there are several theories given to explain this process. From all such theories it is clear that there is a basic tendency of chip curling in all strain hardening materials. Study of the nature and behaviour of chip curl is very essential, if we want to represent or display the chip formation.

The chip curl is a plastic flow phenomena which does not occur in non strain-hardening materials [18]. The initial or natural radius of chip curvature is very small. An originally straight chip undergoes a severe plastic deformation in order to assume its actual shape. Various expressions are available for calculating the initial chip radius. One important analysis about this is given by Rubenstien [19], which gives expression for free chip radius as

$$R = H\, t_1$$

where

$$H = \left[\frac{bK_2^{\gamma+2}}{G(\gamma+2)} \times \frac{1-(1-\alpha')^{\gamma+2}}{\alpha'^{\gamma+2}}\right]^{1/\gamma}$$

γ = exponent of stress-strain relation

K_2 = chip thickness ratio

α' = t_2/depth of the neutral axis

G = $G_T - G_W$ = imbalanced moments acting on the chip

ii. Kinematics of chip curl: A mathematical description of the geometry of chip curl will be extremely complex and the writers have not arrived at any satisfactory solution. At the start when chip length is very small, the chip takes a circular shape with a radius equal to initial chip radius. (When orthogonal cutting is considered). This continues till the chip touches the workpiece surface. But after that chip shape is totally different, though the initially formed circular part retains its shape.

Cook et.al [18] have devised a very simple graphical technique to describe the kinematics of curling. The actual chip geometry is very well represented by this graphical method; Fig. 6.1 , hence it can be said that it explains the mechanism also. The graphical technique can be simply described as:

1. A scale drawing of tool-work-chip geometry is made, at the time when the chip just impinges upon the uncut surface.

2. A transparent overlay is placed over the drawing and the small chip (B-C) is traced.

3. The overlay is then rotated a few degrees clockwise about (A), the centre of initial chip curvature. When this is done

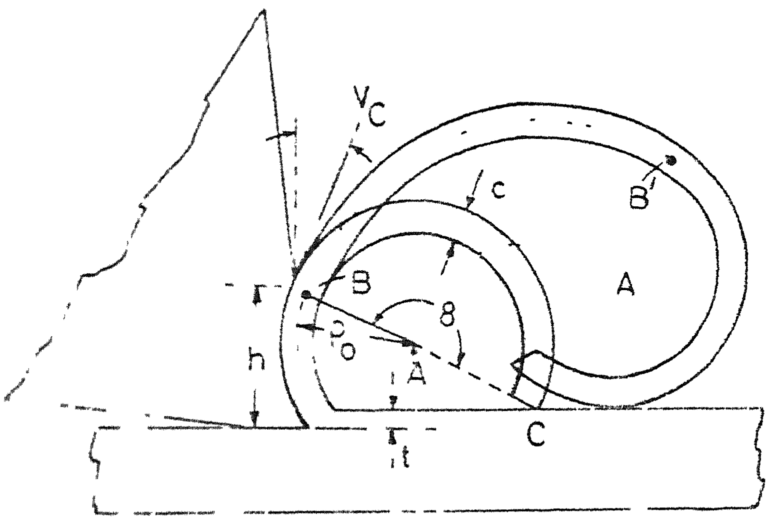


Fig 6.1 Showing how chipsgeometry can be obtained graphically.

(C) is below the work surface.

4. ... overlay is rotated counterclockwise about (B), a ... neutral axis of the chip where chip leaves the ..., until the chip end (C) is just raised to the work surface.

5. Steps iii and iv are repeated. The curve A-A' represents ... centres used in step 3, while B-B' is the locus of centres of rotation for step 4.

In order to demonstrate the manner in which the graphical method does reproduce actual chip contour, Fig. 6.2 shows an actual chip contour (as traced on an optical comparator) and a chip contur is graphically developed. The general agreement is surprisingly good.

The chip shape is not a simple spiral due to the initial circular portion. However as the chip grows it approaches an exponential spiral which is reasonably well represented by:

$$\frac{\rho}{\rho_o} = e^{n_1(\theta' - \theta_o)}$$

where

θ' = total angular chip rotation

θ_o = initial circular chip rotation

n_1 = spiral exponent.

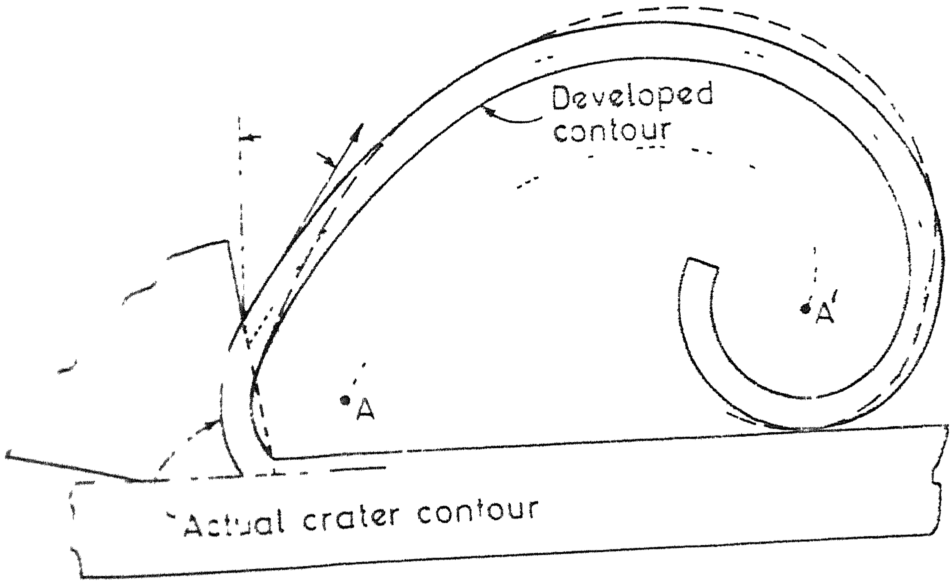


Fig. 6.2 Showing correlation between actual chip shupe and graphically developed shape.

6.2 Display of Chip and Tool:

A tool designer will definitely like to know about the performance of the tool. At present it is not possible for the designer to see chip formation process in the design office itself before actually making a tool and sending it for a test. Here is an attempt to assist the tool designers in this regard.

Because of the practical difficulties and insufficient data available, it is not possible to give a true display of the chip formation process, but the program gives a good approximation in an animated form. It represents a two dimensional (orghogonal) cutting process. For the given tool geometry and work - tool combination, it displays the chip formation process. From the graphical technique given by Cook et.al.[18], it will be clear that it is very difficult to trace or predict the nature of chip. The procedure given is very complicated and being a manual one it has its own limitations. The visualization of chip formation for different combinations and development of chip starting to the chip breaking is impossible. This program gives the designer the freedom to choose the length for which he wants to see the chip formation.

The graphical technique does not have any fixed assumption or suggestion for the initial portion of the chip in which chip and tool are in contact, before the tool develops

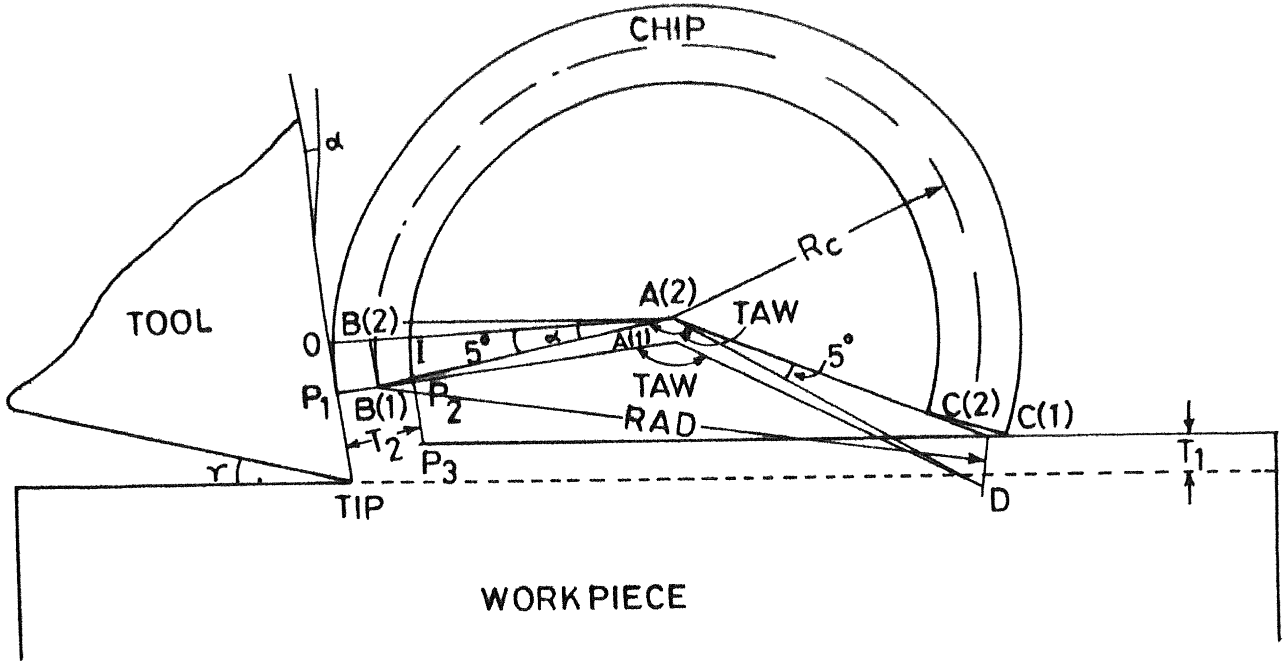


Fig. 6.3 Chip formation - graphical method

crater. In the given programme the chip-tool contact length is the findings of most of the researchers.

The procedure used in the present work is basically the same as graphical method, but there are some additional features. The designer first chooses the check length, which is the total length for which the chip formation is to be displayed. He has to choose the sample length also, it is the unit length which will be added each time for the next stage of chip formation to be displayed. Since this program is an integrated part of the main program for tool design, it automatically takes the values of tool angles, coefficient of friction and the depth of cut. But designer has to give value of initial chip radius. The calculation of chip radius can be made a part of this program, but because of the various different expressions and theories it is better if the designer chooses this option. The program gives freedom to the designer to choose the initial co-ordinates of the tool tip, which offers him a choice of the range in which he will observe the cutting process. Basically there are two types of cutting processes, moving tool and moving workpiece. The program considers both cases and the designer has an option.

6.3 Program Structure:

i. Block diagram Fig.6.4, shows the flowchart of the program developed for displaying the chip formation. In the figure

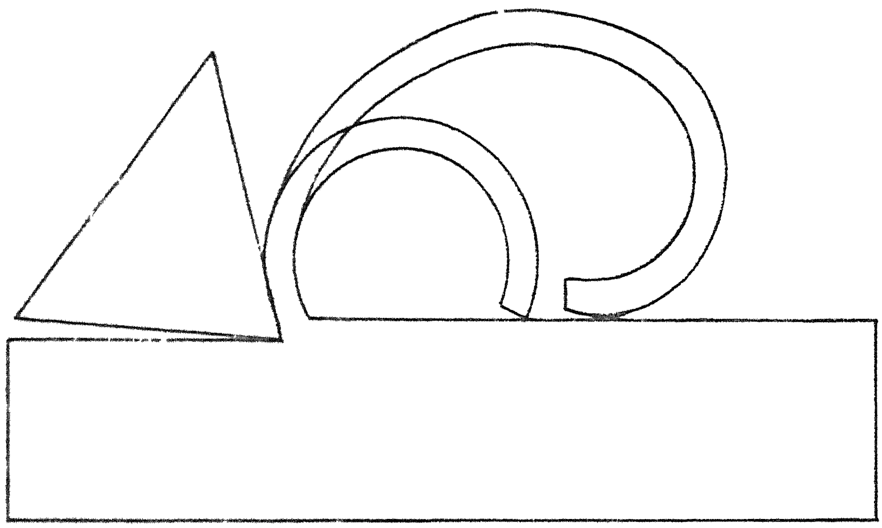


Fig. 6.4 Computer display of chip formation process.

various steps are shown in rectangular boxes, whereas input required and the result obtained have been encircled. The output is the graphic display of chip formation process.

ii. Display of chip formation process:

1. Selecting the option of moving tool or moving workpiece.
2. Reading input values from the terminal.
3. Calculations for shear angle, friction angle and chip thickness.
4. Calculates the chip length and checks it for the range in which it will be. (First is chip-tool contact part, second is the circular portion of the chip and third portion is one in which chip assumes a spiral shape after impinging on the workpiece).
5. In the first portion chip is represented by using three points only.
6. In the circular portion the chip is represented using the chip radius.
7. For the spiral portion a special procedure is followed as given herewith.
8. Angle TAUC suspended by the circular portion at the centre A is calculated.
9. Increament of 5^{o} is given to TAUC, hence chip end D will be below the work surface.
10. Distance BD is calculated.

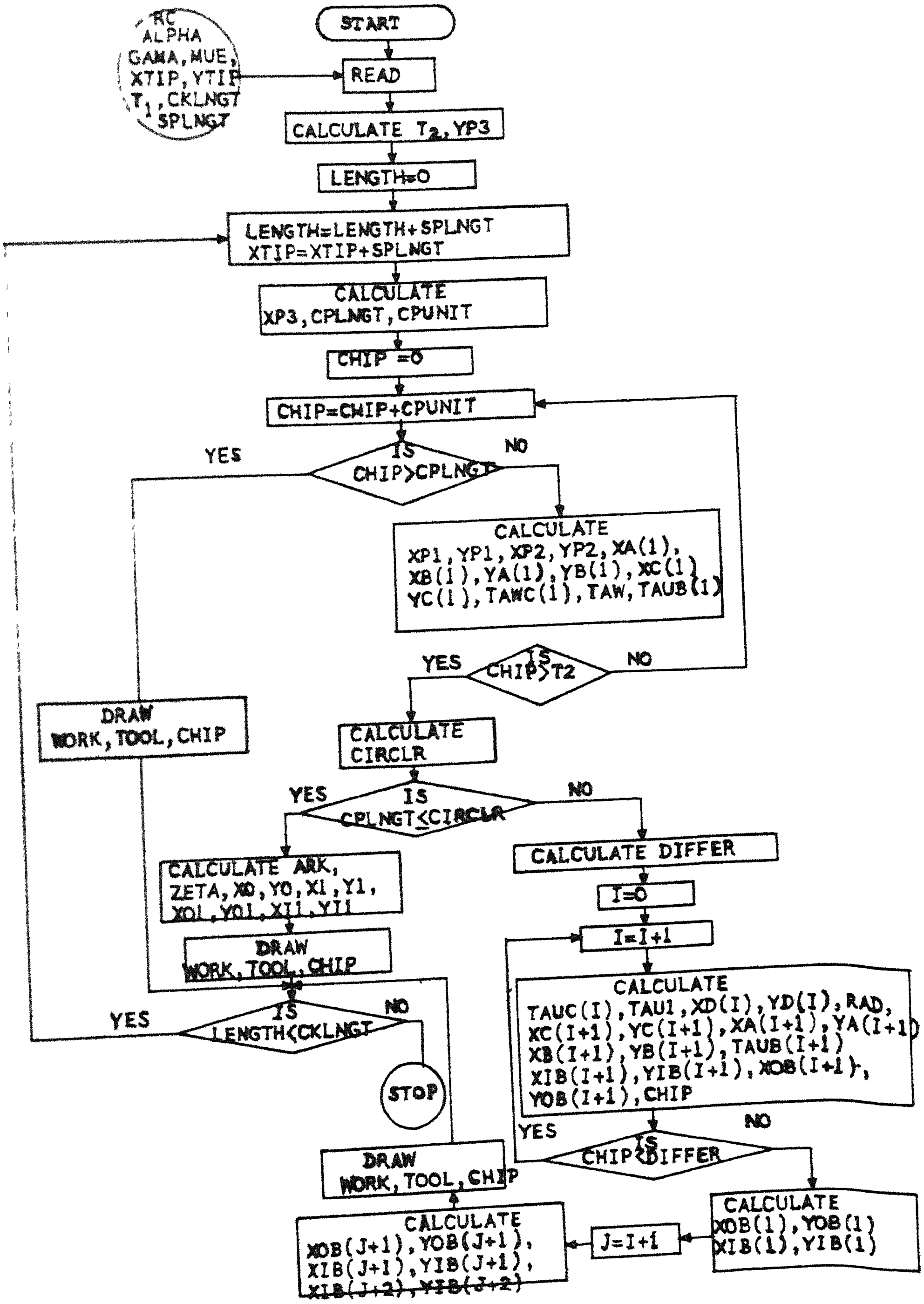


FIG. 6.5 FLOW CHART FOR DISPLAY OF CHIP FORMATION PROCESS-(MOVING TOOL).

11. Taking B as centre and BD as radius, point D is moved counter clockwise to bring it to the work surface.
12. New co-ordinates of point A are calculated.
13. Point B is moved by 5° clockwise, with A as centre.
14. Calculate co-ordinates of the outer and inner chip point
15. Repeat the procedure from i, upto checklength.
16. Call the subroutine to draw tool-work configuration.
17. Join the calculated chip points.
18. Repeat the complete procedure for the different frames.
19. Display all frames one after the other to give an animated display according to the option of moving workpiece or moving tool.

If chiplength exceeds some particular value at which the geometric constraints cause breaking of the chip, the display is automatically stopped. This breaking is because of the reason that though theoretically the shape of the chip is spiral, it is actually not; in the initial circular portion. This circular portion after some time impinges upon the newly developed chip surface thus causing breaking of the chip. But in actual cutting process the chip geometry, metallurgical and other force constraints generally cause breaking of chip much earlier. Because of the insufficient data available about the chip breaking, it was not possible to introduce these factors here. But with reliable data the chip breaking can be easily shown using this program.

CHAPTER 7

SUMMARY

7.1 Results:

i. The output values obtained from the program for free machining steel as work material and H.S.S. tool are-

P_x - 29.618530 Kg

P_y = 63.512680 Kg

P_z = 95.869995 Kg

Power consumption = 1.412160 KW

Surface roughness = 0.003347 MM

Min. Height of the tool= 9.0058997 MM

Min. width of the tool = 5.403538 MM

Back rake angle = 12.0

Side rake angle = 12.0

Side Cutting edge angle= 15.0

End cutting edge angle = 15.0

Side relief angle = 5.0

End relief angle = 5.0

Nose radius = 0.75

Chip breaker width = 2.0 mm.

Chip breaker radius = 0.5 mm.

ii. The results obtained from the multistage optimization of the cutting conditions for the given constraint values are as follows-

Constraint values -

Power =40.0 KW.

Motor Torque =30.0 Kg-M.

Maximum deflection permissible=0.04 mm.

$60 \leq V \leq 90$ m/sec.

$0.125 \leq$ feed ≤ 0.375 mm/rev.

$0.4 \leq$ depth of cut ≤ 2.5 mm.

The objective function being cost of machining.

The output values were-

I cut - N = 210. 344 RPM s = 0.254 mm/rev.

t = 0.775 mm.

II cut - N = 214.871 RPM s = 0.254 mm/rev.

t = 0.775 mm.

III cut- N = 221.353 s = 0.226 mm/rev.

t = 0.650 mm

iii. The results obtained from the optimization of tool geometry parameters are as follows-

The input values of cutting conditions were-

Speed = 50.0 m/min

Feed = 0.2 mm/rev

Depth of cut= 1.85 mm.

Maximum width of cut permissible = 2 mm

Thus the maximum permissible value of side cutting edge angle can be calculated-

$$\phi = \cos^{-1}\left(\frac{t}{b_{max}}\right)$$

$$= 22.33$$

The output values obtained are-

Normal rake angle = 7.1735

Normal clearance angle = 20.3856

Side cutting edge angle = 22.33

From the values of normal rake angle the values of back rake angle and side rake angle can be obtained. If inclination angle = = 6.0, the values of side rake angle and back rake angle will be as follows-

Side rake angle $= \beta = \tan^{-1}(\tan \alpha_o . \cos \phi - \tan \lambda . \sin \phi)$

$= \tan^{-1} (\tan (7.1735).\cos (22.33)- -\tan (6.0).\sin (22.33))$

$= 4.3739.$

Back rake angle $= \alpha = \tan^{-1} (\tan \lambda . \cos \phi + +\tan (\alpha_o . \sin \phi)$

$= \tan^{-1} (\tan (6.0).\cos (22.33) + \tan (7.1735). \sin (22.33))$

$= 8.2527$

From the value of normal clearance we get value of end clearance angle similarly. The values of side clearance angle and end cutting edge angle are not very

critical and are generally chosen. The only condition is that the values should be greater than a minimum which is given to avoid rubbing between the workpiece and the tool.

7.2 Concluding Remarks:

The program can thus be interactively used for designing a single point turning tool. It gives a good substitution for lengthy and tedious tool design procedure. The multistage optimization of the cutting conditions gives optimum values of feed, speed and depth of cut for each cut. Methodology developed for the optimization of tool geometry parameter is qualitative only. But it is clear that there exists an optimum combination of tool geometry parameters. A large number of experiments will be however needed if this is to be actually used. The experiments should be carried out under identical conditions to give the effect of various tool angles. It will be possible then to formulate a very accurate objective function.

The graphic display of various views of the single point turning tool give a clear idea about the structure of the tool. The graphic simulation of chip formation process is a close approximation of actual chip formation process, and gives an idea about the machining before actually doing it. The effect of various rake angles on the chip shape can be very easily seen by just varying some values.

7.3 Recommendations for Further Work:

i. The program can be made more useful by entering data about more work materials or various compositions of material.

ii. The display of the chip formation process can be modified to give actual chip breaking also by considering various conditions under which the chip breaks. This will be very useful because chip breaking is as important as chip formation.

iii. The effect of tool geometry on the exponents of feed speed and depth of cut in the tool life equation can be studied and introduced in the objective function, so as to make the results more accurate.

iv. A special set of experiments can be carried out under identical conditions and the effects of various tool geometry parameters can be studied, to give the exact expressions.

iv. The optimization of tool geometry using stochostic programming can be done, to give an optimum design of turning tool for the working range of speed, feed and depth of cut.

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APPENDIX

Table 2: Recommended Cutting Fluids:

Work Material	H.S.S.	Carbide
Free Machining Steels	LD Cutting Oil HD Water Miscible	Water Miscible Dry
Low Alloy Steels	HD Cutting Oil GP Water Miscible	Water Miscible Dry
Stainless Steels	HD Cutting Oil HD Water Miscible	Water Miscible
H.S.S.	HD Water Miscible HD Cutting Oil	Water Miscible
Cast Iron	GP Water Miscible Dry	HD Cutting Oil HD Water Miscible
Magnesium and Alloys	LD Cutting Oil Specialty Fluid	LD Cutting Oil Specialty fluid
Aluminium and Alloys	LD Cutting Oil GP Water Miscible	Water Miscible
Copper and Alloys	LD Cutting Oil Specialty Fluid	Water Miscible

(Source: Tool and manufacturing engineers handbook, Reference 8)

Table 3: Recommended Cutting Speeds:

		Cutting speed m/min			
		Depth of Cut, mm			
		0.1-0.4	0.4-2.5	2.5-4.5	4.5-10
		Féed mm/rev.			
WORK MATERIAL	TOOL	0.05-0.125	0.125-0.375	0.375-0.75	0.75-1.25
Free Cutting Steels	HSS	- -	75-105	50-75	25-45
	Carb-ide	225-450	180-225	135-180	105-135
Carbon and Low Alloy Steels	HSS	- -	65-90	45-60	20-35
	Carb-ide	210-360	165-210	120-165	60-120
Medium Alloy Steels	HSS	-	60-80	35-50	20-35
	Carb-ide	180-300	135-180	105-135	75-105
High Alloy Steels	HSS	-	50-75	35-50	20-30
	Carb-ide	150-225	120-150	105-135	60-90
Stainless Steels	HSS	-	30-45	25-30	15-20
	Carb-ide	110-150	90-110	75-90	50-75
Cast Iron	HSS	-	25-45	18-36	12-27
	Carb-ide	90-180	45-135	30-105	22-75
Aluminium and alloys	HSS	105-150	65-105	45-66	30-45
	Carb-ide	210-300	135-210	90-135	60-90
Copper and Alloys	HSS	-	80-105	65-80	45-65
	Carb-ide	210-240	180-210	150-180	120-150
Magnesium and Alloys.	HSS	150-225	105-150	80-105	60-80
	Carbi-de	375-600	240-375	180-240	150-180

(Source: Production technology H.M.T.) Reference 14)

Table 4: Recommended Speeds for Ceramic Tools:

(Source: Production Technology H.M.T., Reference 14)

	Depth of cut Over 1.5 mm	Under 1.5mm
	Feed	
WORK MATERIAL	0.4 - 0.8	Under 0.25mm
Carbon and Tool Steels	90-450	150-600
Alloy Steels	90-240	90-420
H.S.S.	30-240	30-300
Stainless Steel	60-300	120-360
Cast Iron	30-240	60-420
Copper	120-240	180-420
Aluminium Alloys	120-6000	180-900
Magnesium Alloys	240-3000	240-3000

Table 5: Selection of Nose Radius:

Depth of cut mm.	Nose radius mm.
Less than 3.0	0.5 - 0.75
3.0-10.0	1.0
10.0-20.0	1.5-2.0
20.0-30.0	2.0-3.0

(Source: Metal cutting theory and practice, Bhattacharya ,Reference

Table 6: Recommended Tool Angles:

rk	Tool	Back Rake Angle	Side Rake Angle	Cutting Edge Angles	Relief Angles
ree Machin- [illegible]	HSS Carbide	12 -2	12 0	15 15	5 5
ow Alloy teels	HSS Carbide	12 -2	12 0	15 15	5 5
tainless teel	HSS Carbide	2 -2	10 0	15 15	5 5
ast Iron	HSS Carbide	5 -2	5 0	15 15	5 5
agnesium	HSS Carbide	20 2	15 10	5 15	5 5
Alminium	HSS Carbide	20 -2	15 0	15 5	5 5
opper	HSS Carbide	5 0	10 6	5 15	8 5

([illegible] logy HMT, Reference 14)

Table 7: Chip Breaker Dimensions:

Depth of Cut mm.	2.0	3.0	4.5	6.0	8.0	10.0	15.0
Width mm.	2.0	2.5	4.0	6.0	8.0	9.0	10.0
Radius mm.	0.5	1.0	1.5	4.5	4.5	5.0	5.5

([illegible] Manual on cutting of metals, ASME, Reference 5)

TABLE 8

Values of constants in Granovsky's Empirical Law

Table 8(a): Values of K_{ϕ}: Effect of Side Cutting Edge Angle

ϕ	$(K_{\phi})_z$		$(K_{\phi})_y$		$(K_{\phi})_x$	
	Steel	Cast Iron	Steel	Cast Iron	Steel	Cast Iron
30°	1.08	1.05	1.63	1.23	0.70	0.63
45°	1.00	1.00	1.00	1.00	1.00	1.00
60°	0.98	0.96	0.71	0.87	1.27	1.14
75°	1.03	0.94	0.54	0.77	1.51	1.20
90°	1.08	0.97	0.44	0.70	1.82	1.28

Table 8(b): Values of K_v: Effect of Cutting Speed

v m/minute	20	40	50	60	80	100	160	200	240
$(K_v)_z$	0.89	0.97	1.0	0.97	0.91	0.87	0.81	0.80	0.795
$(K_v)_{x,y}$	0.70	0.98	1.0	0.91	0.78	0.73	0.6	0.6	0.59

Table 8(c): Values of K_{cf}: Effect of Cutting Fluid

Cutting fluids	(K_{hf}) (z,y,x)
Dry	1
Water	0.97
Emulsion	0.90
Mineral Oil	0.85

Table 8(d): Values of K_r: Effect of Nose Radius

r	$(K_r)_z$		$(K_r)_y$		$(K_r)_x$	
mm	Steel	Cast Iron	Steel	Cast Iron	Steel	Cast Iron
0.5	0.87	0.91	0.65	0.76	1.56	1.32
1.0	0.93	0.95	0.81	0.87	1.24	1.16
1.5	0.91	0.98	0.92	0.94	1.11	1.06
2.0	1.00	1.00	1.00	1.00	1.00	1.00
3.0	1.04	1.03	1.13	1.08	0.70	0.93
5.0	1.10	1.07	1.30	1.20	0.78	0.84

Table 8(e): Values of Transfer Coefficient K_M: Effect of Soft Materials

Materials	K_M
Carbon steel- heat-treated and annealed	1.00
Aluminium (average value)	0.20
Aluminium $\sigma_u = 16$ kg/mm^2	0.15
Aluminium $\sigma_u=25$ kg/mm^2	0.30
Aluminium $\sigma_u=35$ kg/mm^2	0.40
Aluminium $\sigma_u > 35$ kg/mm^2	0.55
Cast iron	0.50

Table 8(f): Values of Material Constant C .

Process	BHN	Steel C_z	Steel C_y	Steel C_x	Cast Iron C_z	Cast Iron C_y	Cast Iron C_x
Turning	$\leq$ 170	27.9	0.0027	0.0212	6.35	0.10	0.16
	> 170	3.57			5.14	0.045	0.051
Parting Grooving	< 170	34.42	-	0.031	8.82	-	0.12
	> 170	4.42					

Table 8(g): Values of Exponent m: Effect of BHN.

Materials	Values of Exponent m $(m)_z$	$(m)_y$	$(m)_x$
Steel	0.35(BHN$\leq$ 170)	2.0	1.5
	0.75(BHN>170)		
Cast Iron	0.55	1.3	1.1

Table 8(h): Values of Exponents p and q: Effect of Depth of Cut and feed.

Process	Steel						Cast Iron					
	p_z	p_y	p_x	q_z	q_y	q_x	p_z	p_y	p_x	q_z	q_y	q_x
Turning	1.0	0.9	1.2	0.75	0.75	0.65	1.0	0.9	1.2	0.75	0.75	0.75
Parting and Grooving	1.0	-	1.2	1.0	-	0.75	1.0	-	1.2	1.0	-	0.75

(Source Tables 8 : Metal cutting theory and practice [illegible]

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